

HYDRAULICS OF RIVER FLOW

UNDER ARCH BRIDGES 001360

JUNE 1964

NO. II

VOL. I

Joint  
Highway  
Research  
Project

by

J. W. DELLEUR

PURDUE UNIVERSITY  
LAFAYETTE INDIANA





# HYDRAULICS OF RIVER FLOW UNDER ARCH BRIDGES

TO: K. B. Woods, Director  
Joint Highway Research Project

June 19, 1964

FROM: H. L. Michael, Associate Director  
Joint Highway Research Project

Project: HPS-R-1 (36)  
File: 9-8-2

The Final Report on the project "Hydraulics of River Flow Under Arch Bridges" is attached. The title of the report is the title of the project and it has been prepared by Dr. J. W. Delleur, under whose direction most of the study has been performed.

This project was initiated in April 1958 and will be terminated upon acceptance of this final report by the cooperating agencies. During the six years of the project many monthly progress reports and seven larger progress reports were submitted. The attached report summarizes all the work performed during the entire project period and is in two volumes with Volume II containing only the figures.

This research has provided information on the backwater effects and energy losses of arch bridge constrictions with rigid boundaries. The information provided should be of great value to highway engineers in evaluating the problems associated with arch bridge crossings of streams.

The report is submitted for the record and will also be sent to the Indiana State Highway Commission and the Bureau of Public Roads for their acceptance of this Final Report on this project, subject of course to their review and comments and any subsequent action required.

Respectfully submitted,

*Harold L. Michael*

Harold L. Michael, Secretary

HIM:bc

Attachment

Copy:

F. L. Ashbaucher  
J. R. Cooper  
W. L. Dolch  
W. H. Goetz  
F. F. Havey  
F. S. Hill  
G. A. Leonards

J. F. McLaughlin  
R. D. Miles  
R. E. Mills  
M. B. Scott  
J. V. Smythe  
E. J. Yoder





Final Report

HYDRAULICS OF RIVER FLOW UNDER ARCH BRIDGES

Vol. I

by

J. W. Delleur  
Professor of Hydraulic Engineering

Joint Highway Research Project

Project: HPS-R-1(36)

File: 9-8-2

Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project  
Engineering Experiment Station  
Purdue University

in cooperation with

Indiana State Highway Commission

and the

Bureau of Public Roads  
U S Department of Commerce

Released for Publication

Not Reviewed by


Subject to Change

Purdue University

Indiana State Highway Commission  
or the  
Bureau of Public Roads

Lafayette, Indiana

June 19, 1964



Digitized by the Internet Archive  
in 2011 with funding from  
LYRasis members and Sloan Foundation; Indiana Department of Transportation



## TABLE OF CONTENTS

	Page No.
I. I-1 Preface and Acknowledgements	1
I-2 Bibliography of Chapter I	5
II. <u>Literature Abstracts</u>	
II-1 Constriction and Backwater	7
II-2 Expansion Losses	11
II-3 Submergence	15
III. <u>Theoretical Analysis</u>	
III-1 Flow Configurations at an Open Channel Constriction	18
III-2 Basic Equations	20
III-3 Types of Flow at a Bridge Constriction	25
III-4 Discrimination Between Free Surface Flow and Orifice Flow	28
III-5 Flow Class 1-Subcritical Flow Through Unsubmerged Constriction	30
a) General Considerations	30
b) Momentum Equation for Diverging Flow	32
c) Energy Equation for Converging Flow	35
d) Graphical Solution of Backwater Due to a Constriction	37
III-6 Flow Class 2-The Flow Goes Through Critical in the Constriction	38
a) Geometric Properties of Semi-Circular and Circular Segment Arches	38
b) Limiting Backwater	39
III-7 Discharge Equation	42
a) Free Surface Flow	42
b) The Equation of Discharge for Orifice Flow	45
III-8 Energy Loss in the Constriction	48
III-9 Backwater Ratio Equations	52
III-10 Dimensional Considerations	58
a) Dimensional Analysis	58
b) Definition of Channel Opening Ratio and Channel Width Ratio	60





## III-11 Definition of Test Geometries

63

## III-12 Bibliography of Chapter III

68

IV. Preliminary Tests (by S. T. Husain and A. A. Sooky)

## IV-1 Small Flume, Models and Test Conditions

69

## IV-2 Test Results

73

V. Experimental Equipment

## V-1 Design and Construction of Testing Flume

75

## V-2 Water Supply and Measurement

80

## V-3 Measuring Equipment

81

## a) Instrument Carriage

81

## b) Point gage

81

## c) Prandtl Tube

82

## d) Variable reluctance pressure transducer

82

## e) Calibration of velocity probe

82

## V-4 Boundary Roughness Analysis in Large Flume

84

## a) Smooth boundaries

84

## b) Rough boundaries

86

## V-5 Bibliography of Chapter V

91

VI. Procedure and Data Processing for Free Surface Flow Tests

## VI-1 Selection of variables

92

## VI-2 Obtention of uniform flow

94

## VI-3 Free surface measurements

95

## VI-4 Data Processing

96

## VI-5 Four variables graphical multiple correlation

98

VII. Free Surface Flow Test Results

## VII-1 Geometry Ia - Smooth Boundaries

101

## a) Introduction

101

## b) Tests by H. J. Owen

101

## c) Tests by P. F. Biery

104





	Page No.
VII-2 Geometries Ia and Ib - Rough Boundaries - Tests by P. F. Biery	105
a) Test selection	105
b) Test data	105
c) Test results	106
α) Backwater ratio and discharge coefficient	106
β) Location of the points of maximum backwater	107
γ) Determination of minimum depth	108
δ) Regain curve length	108
ε) Comparison of roughness effects	108
ζ) Comparison of bridge length effects	109
η) Surface topography	109
θ) Velocity profiles	110
κ) The generalized backwater equation and head loss coefficient	111
VII-3 Geometry II - Tests by S. Lippai and T. P. Chang	114
VII-4 Geometry III - Tests by T. P. Chang	117
VII-5 Geometry IV - Tests by T. P. Chang	119
VII-6 Geometry Va - Tests by T. P. Chang	120
VII-7 Geometry Vb - Tests by T. P. Chang	121
VII-8 Geometry VI - Tests by T. P. Chang	122
VII-9 Geometry VII - Tests by T. P. Chang	123
VII-10 Bibliography of Chapter VII	124
<u>Submerged Flow Test Results</u> (Tests by O. Eikerl)	
VIII-1 Test Selection	125
VIII-2 Definitions - fully submerged and partly submerged flow	134
VIII-3 Geometry Ia - Smooth Boundaries	135
a) Coefficients of contraction, discharge and velocity for free jet outflow	135



b) Velocity distribution at vena contracta for free jet outflow	136
c) Generalized backwater equation - outflow fully and partly submerged	137
d) Discharge coefficient for free, submerged and partly submerged outflow	138
VIII-4 Geometry Ib - Smooth boundaries	139
VIII-5 Geometries Ia and Ib - Rough boundaries	140
a) test data	140
b) comparison between smooth and rough tests	141
VIII-6 Geometry Vb - Rough boundaries	141
VIII-7 Geometry VI - Rough boundaries	143
VIII-8 Geometry VII - Rough Boundaries	144
VIII-9 Head losses due to submerged arch bridge constrictions	145
VIII-10 General backwater equations	146
VIII-11 Conclusions - submerged flow tests	148
 <b>IX. <u>Field Work</u></b>	
IX-1 Preliminary Field Survey of Sites for Model-prototype comparison of the hydraulic of arch bridge constriction by Messrs. T. P. Chang and J. T. Strange, Indiana State Flood Control and Water Resources Commission.	150
IX-2 Summary of information on bridge sites.	154
IX-3 Preliminary study of indirect determination of flood discharge from contracted bridge opening and high water marks, by I. P. Wu, Indiana Flood Control and Water Resources Commission.	165
Appendix A - Notations	170
Appendix B - List of Tables and Figures	175





## I. PREFACE AND ACKNOWLEDGMENTS

This report completes a general program sponsored by the State Highway Department of Indiana and the U.S. Bureau of Public Roads at Purdue University on the Hydraulics of River Flow under Arch Bridges.

The project has been active from April, 1958, to December, 1963. From the beginning to June, 1961, and from September, 1962 to December, 1963, the project was under the direction of Professor J. W. Delleur. From June, 1961, to September, 1963, it was under the direction of Professor G. H. Toebes. Several reports on different phases of the study have been submitted. In 1958, Mr. S. T. Husain<sup>1</sup>\* reported his work, "Preliminary Model Investigation of Hydraulic Characteristics of River Flow Under Arch Bridges". This was an investigation in a 12 foot long, 6 inches wide tilting flume with smooth boundaries which led, in 1959, to the building of a 64 foot by 5 foot by 2 foot, all steel tilting flume. The design of the 64 foot flume was undertaken by Mr. H. J. Owen. This, along with the first tests in this flume was described in the report entitled: "Design and Construction of Hydraulic Flume and Backwater Effects of Semi-circular Constrictions in Smooth Rectangular Channel", by H. J. Owen and J. W. Delleur.<sup>2</sup> Mr. A. A. Sooky<sup>3</sup> derived an equation for the discharge through a sharp edged semi-circular constriction for the case of free surface flow through the opening. He also extended Mr. S. T. Husain's preliminary tests in the 6 inch wide flume to include the effect of rough boundaries. The work of Husain, Sooky and Owen was summarized in a report entitled, "Hydraulics of River Flow Under Arch Bridges - A Progress Report".<sup>3</sup>

In 1960 and 1961, Mr. P. F. Biery undertook an investigation of artificial roughness in the 5 foot wide flume and studied single span arch bridge constrictions with free surface flow. The experiment did not include skew, eccentricity or entrance rounding, but tests were made with smooth and rough boundaries. A backwater equation

---

\*Superscripts refer to references in the bibliography.



was obtained together with a bridge design procedure for free surface flow through the opening, and a procedure for indirect discharge calculation from high water marks. The work was summarized in two reports entitled: "Hydraulics of Single Span Arch Bridge Constrictions"<sup>4</sup> and "Discussion on Roughness Spacing in Rigid Open Channels"<sup>5</sup> and both authored by P. F. Biery and J. W. Delleur. These reports were later published in the Journal of the Hydraulics Division of the American Society of Civil Engineers.<sup>6</sup>

In 1961 and 1962, Messrs. S. Lippai and T. P. Cheng investigated the free surface geometry due to dual bridges, wing walls, eccentricity, skew and arch segments. No formal report was submitted on the works of Messrs. S. Lippai and T. P. Cheng. A summary of this work was presented in the monthly progress reports prepared by Professor G. H. Toebes.

In 1962 and 1963, O. Eikeri undertook the study of the effect of submergence of arch bridge constrictions on backwater superrelevation. His work was presented in a report entitled "Hydraulics of Submerged Arch Bridges"<sup>8</sup>. The experimental data of Messrs. P. F. Biery, S. Lippai and T. P. Cheng were reanalyzed in the fall of 1963. The necessary computer programs and plots were prepared by M. Mushtaq.

Also in 1962, a program of field verification was undertaken. Messrs. T. P. Cheng and J. T. Strange of the Indiana Flood Control and Water Resources Commission investigated over 100 arch bridge sites and selected 10 field verification sites<sup>9</sup>. Air photographs of 9 of these sites were made by the State Highway Department of Indiana. Topographic maps were prepared from these photographs in the Air-Photo Laboratory at Purdue University under the direction of Professor R. Miles.

The research reported herein was performed in the Hydraulics Laboratory, School of Civil Engineering at Purdue University, under the auspices of the Joint Highway Research Project, Professor K. B. Woods, Director and Professor H. Michael, Associate Director.





The present report summarizes the work done during the entire duration of the project. It includes the following parts: a literature abstract, a theoretical analysis, a description of the experimental procedure used in the testing program, and finally the presentation and analysis of the test data.

Regarding the motivation for studying the hydraulic characteristics of arch bridges, the following question could well be asked: How many arch bridges are there in the entire United States? Although this figure is probably unknown, Indiana alone has about 900 arch bridges, over 100 of these are in Marion County and adjacent counties. This explains the particular interest that has existed in Indiana regarding the hydraulics of arch bridges.

By increasing the backwater upstream from the bridge site, many of these bridge constrictions cause additional flooding during high flow; people and valuable property are endangered. In recent years, the problem of minimizing the backwater effect due to bridge constriction has become increasingly important. The highway engineers are faced with a multisided problem; not only do they have to build bridges to convey a specified traffic volume and are safe with respect to flooding, but they also must find the most economic design possible. It is common knowledge to the highway engineer that a bridge crossing will interfere with the natural flow of the stream and will result in a rise of stage upstream from the bridge and in an increase in velocity through the bridge constriction. The engineers are also aware of alternatives of the inexpensive soil fill compared to a structural span. The optimum design is the shortest span that will not cause damage due to stage increase during serious flood conditions. In order to meet these requirements, exhaustive investigations were undertaken to study the hydraulic characteristics of the water flow through different bridge constrictions.

The other motivation for the study of hydraulics of arch bridges is the indirect determination of flood discharge from high water marks. The existing methods are



not applicable to the arch geometry. Due to the large number of arch bridges in Indiana, particularly on small streams, many of which are ungaged, the determination of peak discharge from backwater observation at bridge site would provide a valuable addition to the knowledge of small watershed hydrology.

The scope of the present research is limited to the study of the backwater effects and energy losses through arch bridge constrictions with rigid boundaries. In other words the effects of scour at the bridge site are not considered. This is not an excessive limitation as a correction curve for backwater with scour is available in the literature<sup>10</sup>.



## BIBLIOGRAPHY OF CHAPTER 1

1. Husain, S. T., "Preliminary Model Investigations of Hydraulic Characteristics of River Flow Under Arch Bridges", Masters Thesis, Purdue University, 1959.
2. Own, H. J. and Delleur, J. W., "Design and Construction of Hydraulic Flume and Backwater Effects of Semi-Circular Constrictions in a Smooth Rectangular Channel", Joint Highway Research Project No. 3, 1960. Also submitted by H. J. Owen as M.S. Thesis, Purdue University, 1960.
3. Sooky, A. A., Husain, S. T., Owen, H. J. and Delleur, J. W., "Hydraulics of River Flow Under Arch Bridges - A Progress Report", Progress Report submitted to the Board of the Joint Highway Research Project, May 14, 1959, Purdue University, also published in the Proceedings of the 45th Road School, Series No. 100, Purdue Eng. Exp. Station, Lafayette, March 1960.
4. Biery, P. F., and Delleur, J. W., "Hydraulics of Single Span Arch Bridge Constrictions", Joint Highway Research Project Report No. 4, May 1961, also submitted by P. F. Biery as M.S. Thesis, Purdue University, 1961.
5. Biery, P. F. and Delleur, J. W., "Discussion - Roughness Spacing in Rigid Open Channels", Joint Highway Research Project Report No. 21, June 1961.
6. Biery, P. F. and Delleur, J. W., Discussion on "Roughness Spacing in Rigid Open Channels", Journal Hydraulics Division, ASCE, Vol. 87, HY5, 1961, also in Trans. ASCE, 1963, Vol. 128 Part I, p. 372.
7. Biery, P. F. and Delleur, J. W., "Hydraulics of Single Span Arch Bridge Constrictions", Journal Hydraulics Division, ASCE, Vol. 88 HY5, March 1962.
8. Eikeri, O. and Delleur, J. W., "Hydraulics of Submerged Arch Bridges", Joint Highway Research Project, Report No. 35, December, 1963; also submitted by O. Eikeri as M.S. Thesis, Purdue University, 1964.
9. Cheng, T. P. and Strange, J. T., "A Preliminary Field Survey of Sites for Model-Prototype Comparison of Hydraulics of Arch Bridge Constrictions", Indiana Flood Control and Water Resources Commission, November 1962.
10. Bradley, J. N., "Hydraulics of Bridge Waterways", U. S. Bureau of Public Roads, U.S. Government Printing Office, August, 1960.





## II. REVIEW OF LITERATURE

To the author's knowledge there is no previous systematic investigation of the hydraulic characteristics of arch bridges in particular. There is, however an extensive body of literature on the hydraulics of bridge constrictions, on open channel constrictions in general, on culverts and on the fundamental aspects of the mechanics of contracting and expanding streams.

An annotated bibliography covering some of the most recent literature is given below. This bibliography was compiled by the author as part of his activity in the Task Force on Hydraulics of Bridges of the American Society of Civil Engineers.



## I. CONSTRICTION AND BACKWATER

BRADLEY, J. N. Use of Backwater in Design of Bridge Waterways. Pub. Roads Vol. 30 No. 10 Oct. 1959. pg. 221-6.

"Investigations carried out by Division of Hydraulic Research Bur. Pub. Roads centered on determination of backwater produced by bridges. Scour at bridge abutments, scour around piers, and methods for alleviating scour; research results, design information derived and application of bridge backwater to waterway design; data presented are based on experimental backwater studies using hydraulic models and field measurements", from Engr. Ind. 1960, pg. 160. For a more detailed discussion see Bradley, "Hydraulics of Bridge Waterways".

BRADLEY, J. N., Hydraulics of Bridge Waterways. U.S. Dept. of Commerce. Bureau of Public Roads. Govt. Printing Office. 1960

This report gives the hydraulic design criteria for bridge waterway design and for the computation of backwater caused by bridges, and is written for highway departments engineers. Design procedures and illustrative problems are given for normal crossing, dual bridges, skew crossing, eccentric crossing, abnormal state discharge, and backwater with scour. The methods of computing the backwater are based almost entirely on model tests conducted at Colorado State University (see Liu, Bradley and Plate)

CHOW, VEN TE, Open Channel Hydraulics. McGraw-Hill Book Company, 1959.

In addition to being the most recent and comprehensive text on hydraulics of open channels, Professor Chow's book contains a chapter on "Flow Through Nonprismatic Channel Sections", (Chapt. 17). A detailed summary (Art. 17-16) with complete set of figures of the work of Kindsvater Carter and Tracy, (reproduced from U.S.G.S. circular 284, 1959) gives all the necessary information to calculate the discharge through constrictions, or the backwater ratio due to bridge constrictions.

GRAGWALL, JR. J. Indirect Methods of Discharge Measurement. Proceedings 6th Hydraulics Conference 1955 State University of Iowa. Studies in Engineering-Bulletin 36, 1956.

The 1951 flood in the Kansas river basin is taken as an example to discuss the necessity for indirect discharge measurements. The indirect methods are classified in four groups: 1) the slope area, 2) the contracted opening, 3) the flow through culvert, 4) the flow over dam. Each method is discussed briefly.

For a more detailed discussion of indirect discharge measurement at bridge constrictions see Kindsvater, Carter, and Tracy, "Computation of Peak Discharge at Contractions".





HENRY, H. R. Discussion on "Backwater Effects on Open Channel Constrictions". Trans. ASCE, 120, 1013-1017 (1955)

By simultaneous use of the momentum equation and the specific energy relation both in dimensionless form, Mr. Henry obtains graphically a theoretical solution for the backwater ratio, thus eliminating the trial and error calculation required by the method of Tracy and Carter (see also Ven Te Chow, Open Channel Hydraulics, example 17-3). The effect of the roughness on the decrease of momentum occasioned by boundary shear in the zone of expansion downstream of the constriction is compared to the roughness effect on the loss of energy on the contracting flow upstream of the constriction.

IZZARD, C. F. Discussion on "Tranquil Flow" by C. E. Kindsvater and R. W. Carter. Trans., ASCE, Vol. 120, pg. 985-89. 1955.

The experiments of Kindsvater and Tracy on "Tranquil Flow through Open-Channel Constrictions", were limited to the case of a horizontal bed. Izzard extends the analysis to the case of sloping channels, and making use of experimental data of Tracy and Carter ("Backwater Effects of Open-Channel Constrictions") he shows that the backwater of the constriction may be expressed approximately as the product of a velocity head (velocity at normal depth in downstream section of constriction) times a coefficient which depends primarily on the contraction ratio of the constriction. Whereas Kindsvater and Tracy were concerned with the problem of estimating the discharge from measurement of water levels in the vicinity of a channel constriction, Izzard is concerned with the reverse problem of estimating the backwater caused by a channel carrying a known flow at normal depth.

IZZARD, C. F. Discussion on "Backwater Effects of Open Channel Constriction" by H. J. Tracy and R. W. Carter. Trans. ASCE Vol. 120 pg. 1008-13. 1955.

The paper by Tracy and Carter is analyzed from the highway engineer viewpoint which is that of calculating expected backwater elevations due to floods of various frequencies. As the accuracy of the flood peak estimates is seldom better than  $\pm 20\%$ , simplifications may be introduced in the backwater calculation. The following simplification is proposed by Izzard. Neglecting minor effects (roughness, and length of constriction) the ratio of the maximum backwater depth upstream of the constriction to the normal depth in the uncontracted channel may be correlated to the contraction ratio and the velocity head in the constricted section. The velocity head in the constricted section is based on the area at normal depth.

IZZARD, C. F. and BRADLEY, J. N. Field verification of model tests on flow through highway bridges and culverts. Proc. 7th Hydr. Conf. Iowa Inst. of Hydr. Res. June 1958, Iowa City, Iowa, State University Iowa 1959, pg. 225-43. AMR 13-4641. Sept. 1960.

The paper reports on comparison of prototype measurements with computed values, derived from model tests for backwater caused by bridges, scour at bridge abutments, and head-discharge characteristics of culverts. Computed and measured values of the drop in water level across the bridge embankment is given for ten sites, two of which are for submerged deck girder. The smallest error is 0.5%, the largest is 13%.





KINDSVATER, C. E.; CARTER, R. W.; TRACY, H. J. "Computation of Peak Discharge at Contractions. USGS - Circular 284, 1953.

This report gives a procedure for computing subcritical peak discharges at contractions based on laboratory studies. The discharge formula given includes a discharge coefficient which may be obtained from sets of curves which contain the essential geometric and hydraulic factors governing the flow at a constriction. The factors are: the contraction ratio, the relative length of the abutment, the Froude number, the entrance rounding, the abutment chamfers, the angularity of the constriction, the side depth at abutments, the side slope of the abutment, the eccentricity of the constriction, the bridge submergence, and bridge piles and piers. The primary variables are the contraction ratio and the relative length of the abutments. Standard values of the discharge coefficient as a function of the primary variables are given for four types of geometries: 1) vertical embankments and vertical abutments; 2) sloping embankment and vertical abutments; 3) sloping embankments with sloping abutments; 4) sloping embankments with vertical abutments with wing walls. The standard value of the discharge coefficient is then multiplied by adjustment coefficients, which take into account the effect of the remaining variables, to obtain the discharge coefficient. Detailed field and office procedures are given.

See also: Kindsvater and Carter, "Tranquil Flow through Open-Channel Constrictions" -, for a summary including working curves see Ven Te Chow, "Hydraulics of Open Channels".

KINDSVATER, C. E. and CARTER, R. W., "Tranquil Flow through Open-Channel Constrictions". Trans. ASCE 120, 955-992, 1955.

A practical method of solving the discharge equation for tranquil flow of water through open channel constrictions is described. The functional relationships between the coefficient of discharge and the principal independent variables (contraction ratio, length of contraction, Froude number, entrance rounding, eccentricity of opening, angularity and guide walls) is presented from experimental data. Boundary conditions considered include vertical constrictive elements, channel cross-sectional shapes and roughness pattern. Within the limits tested the proposed computation procedure yields satisfactory results. Tests were run in a horizontal flume. See also the discussion by C. F. Izzard. (adapted from author's conclusions).

LANE, E. W. "Experiments on the Flow of Water through Contractions in an Open Channel. Trans. ASCE, 83, 1149 (1919 - 1920).

This is probably the first laboratory study on open channel constriction in the U.S. The Froude numbers used are higher than those usually found in bridge waterways. There is a limited number of boundary shapes. Experiments were made in four different flow contractions, namely rounded-edge plate, sharp edge plate, short flume, Venturi flume. Coefficients of discharge were first computed using D'Aubuisson's and Weisbach's formulas. Based on the experimental data a general equation of contraction was developed. The results of flume tests were presented in detail and discussed.

LIU, H. K; BRADLEY, J. N.; PLATE, E. J. "Backwater Effects of Piers and Abutments." Rept. CER 57 HKL 10; Colorado State Univ. 1957.

This is the final report of a project undertaken at Colorado State University in cooperation with the Bureau of Public Roads, U.S. Dept. of Commerce. Maximum backwater due to bridge constriction is given for simple normal crossing, abnormal stage-discharge condition, dual bridge crossing, skew crossing, eccentric crossing piers, partially submerged bridge girders. The water surface profiles, coefficient of contraction, location of maximum backwater, are presented. This report is perhaps the most comprehensive work on hydraulics of bridge constrictions in the American technical literature.





NAGAI, S., On the two-dimensional analyses of suddenly contracted flows. Houille Blanche. Nov., 1950. Pg. 662-73. AMR 7-1849

Position of contraction in suddenly contracted flows is determined by use of the Schwarz-Christoffel theorem. Study is made for flows about a suddenly contracted pipe and about that having a round corner. The position of contraction is approximately given with determination of the stationary points of vortex center. Corner radius can be found by which vortex will vanish.

TRACY, H. J., CARTER, R. W. Backwater Effects of Open Channel Constriction. Trans. ASCE 120, 993-1018. 1955.

A method of computing the backwater due to open channel constriction is given. It is based on empirical discharge coefficients and on a laboratory investigation of channel shape, constriction geometry and influence of channel roughness. The solution involves the computation of water-surface drop through the constriction and the determination of a factor which is the ratio of backwater to water surface drop. This ratio is shown to be a function of channel roughness, per centage of channel contraction, and constriction geometry. See also the discussion by Izzard. (adapted from author's synopsis).



## II. EXPANSION LOSSES

ALBERTSON, M. L., JENSEN, R. A., DAI, Y. B., ROUSE, H. Diffusion of submerged jets. Trans. ASCE Vol. 115 (1950) pg. 639-697.

This paper deals with the turbulence generated at the edges of a free air jet issuing from orifices and slots. Results are given of measurements of the distribution of the longitudinal velocity and of turbulence characteristics. Of particular interest to bridge hydraulics is the discussion by H. R. Henry (1950) on flow under sluice gates.

ARCHER, W. H. Experimental Determination of Loss of Head due to Sudden Enlargement in Pipes. ASCE Trans. Vol. 76 (1913) pg. 999.

Sudden expansion head loss:

$$h = \frac{1.098 (\bar{U}_1 - \bar{U}_2)^2}{2g}$$

where  $\bar{U}_1$  and  $\bar{U}_2$  are the mean velocities in the upstream and downstream conduits.

BLANCHET, C. Sur Le Probleme Des Rencus Et Des Pertes De Charge Produits par Les Singularities Dans Les Canaux Et Rivers. Houille Blanche No. 1, Nov. 1945 - Jan. 1946. pg. 39-62.

"Problem of turbulence and loss of head caused by obstructions in channels and rivers; turbulence curves related to curves of specific energy; influence of sill at channel bed and of contraction of cross section area on kinetic energy; results of study can be applied only to channels or rivers of stable bottom not liable to form deposits". From Engr. Ind. 1946 pg. 428.

CHATURVEDI, M. C. Flow Characteristics of Axisymmetric Expansions. Jour. of the Hydraulics Division ASCE, Vol. 89-HY3; May 1963.

Characteristics of flow for four abrupt expansions with half angles of 15°, 30°, 45° and 90° have been determined by a combination of analytical and experimental means. The transformation of mean energy, the rate of production of turbulence, and the rate of dissipation of turbulence energy are determined. The evaluated head-loss results from the air-duct studies are checked by independent measurements in a water-pipe assembly. The kinetic energy of the mean motion, kinetic energy of turbulence, pressure distribution, turbulence production, and turbulence shear are presented in the form of their spatial distribution, for all expansion angles. Head loss in abrupt expansions is given for different angles of separation; for 90° (half angle) the head loss coefficient is practically equal to that obtained in the assumption of constant pressure at the inlet section and one-dimensional analysis ( p. 80 and Fig. 13). The variation of the head loss with changing expansion ratio is considered (p. 89 and Fig. 20).





DAVIDIAN, J., CARRIGAN, P. H. JR., SHEN, J. (USGS) Flow through Opening in Width Constrictions. Water Supply Paper 1369-D, 1962, p. 91-122. plate.

"Flow pattern at constrictions with 2 to 7 openings; laboratory experiments and analysis were directed toward development of methods for computing discharge through multiple opening constrictions, apportioning given total discharge among several openings and predicting backwater caused by constrictions". Engr. Index 1962.

DELORME, A. Considerations Sur Les De Bouches Des Petits Ouvrages Sous Routes. Annales Des Ponts Et Chaussées. Vol. 129. No. 2. March-April 1959. p. 141-67.

"Water passages under small road bridges; size of underpass is often over-dimensioned, because formulas of calculation use too high safety factor; it is recommended that permissible factor of incidence of submersion should be defined by considering possible damage due to submersion; calculations should be based on flood statistics, also law of large values; practical applications." Engr. Ind. 1959, p. 171.

GIBBINGS, J. C., DIXON, J. R. Two-Dimensional Contracting Duct Flow. Quart. J. Mech. Appl. Math. 10, 1, 24-41, Feb. 1957. AMR 10-2954. Sept. 1957.

This paper is primarily for wind tunnel design dealing with potential flow through two-dimensional contracting channels of finite length. Method of eliminating adverse velocity gradient along channel wall was presented in great detail. A numerical example is given.

HENRY, H. R. Discussion on Submerged Jets. Transactions, ASCE, Vol. 115 (1950) p. 687.

This is a discussion to a paper by M. I. Albertson, Y. B. Dai, R. A. Jensen and H. Rouse on diffusion of submerged jets. The effect of boundary conditions different from those used in the main paper are investigated. These, for the case of the flow under a sluice gate, are the effects of the free surface i.e. gravitational effect and the presence of a solid boundary, i. e. the flume floor, instead of a plane of symmetry of a two-dimensional jet. Hydraulic design conclusion: Experimental discharge coefficients for the flow under a sluice gate are given in terms of a dimensionless gate opening, a dimensionless tailwater depth and the orifice Froude number (Fig. 35, p. 691). The expansion of the jet (which is limited by a fixed lower boundary and by a free surface upper boundary) is reported to have a slope of 1 on 6 approximately.

KINDSVATER, G. E. Energy Loss Associated with Abrupt Enlargements in Pipes. USGS. Water Supply Paper 1369-B-1961.

In connection with the USGS study of hydraulics of bridge-waterways, an experimental investigation was made of the flow of water through abrupt concentric enlargements in circular pipes. Particular attention is paid to the influence of pipe-wall roughness and to methods of computing the energy loss resulting from enlargements. The conventional method of computing the energy loss from the Borda-Garnot equation was found adequate for practical use.





PETERS, H. Conversion of Energy in Cross Sectional Divergences Under Different Conditions of Inflow". NACA TM 737, 1934.

Hydraulic design conclusion: Super imposing a spiral motion on the flow entering an expansion increased the efficiency, as the rotational motion delays the separation.

ROUSE, H. Energy Transformation in zones of separation. Proceedings 9th IAHR Conf. Durbrounik, 1961.

The integrated equations of momentum and of mean energy are examined for the case of two-dimensional flow over a normal wall, and attention is given to the variation of the sum of the terms of Bernoulli equation along a streamline in either the primary flow or the zone of separation.

This paper establishes some of the theoretical background on the mechanism of flow separation used in the experimental studies of Chaturvedi (1963).

ROUSE, H. Repartition de l'energie dans les Zones de Decollement. La Houille Blanche No. 3, May 1960 and No. 4, June, 1960.

Distribution of energy in regions of separation

Described in the present paper is the determination of the mean and secondary patterns of axisymmetric flow for two comparable boundary forms: the abrupt inlet and the blunt shaft.

Measurements available for analysis included the distributions of mean velocity, mean pressure, longitudinal and radial intensities of turbulence, turbulent shear, and longitudinal intensity gradient. Through use of the equations of momentum and of energy for the mean and the secondary motion, the measured distributions were adjusted to yield the required balance of the essential terms in the equations, thus yielding results in general accord with physical requirements. These are presented in the form of the flow patterns. (from author's abstract)

TULTS, H., Flow expansion and pressure recovery in fluids. Transactions ASCE, Vol. 121, 1956, Pg. 65. (AMR 8-2394. Aug. '55)

Investigating the possibility of improving the pressure recovery in flow expansions, author observed visually the separation phenomena and measured the development of velocity profiles and pressure distribution in a gradual unilaterally expanding two-dimensional rectangular test canal with varied divergence from zero degrees to 20 degrees in range of Reynolds number  $5 \times 10^4$  to  $3 \times 10^5$ .

A simple analytical dependency is established between the angle of divergence and the rate of separation at which the maximum pressure recovery in each section occurs. This permits us to predict the optimum divergence for any required rate of gradual expansion.



VALLENTINE, H.R., Flow in rectangular channels with lateral constriction plates, Houille Blanche 13, 1, 75-84, Jan.-Feb. 1958. (AMR 12-834.)

Characteristics of flow in a rectangular channel with sharp-edged lateral constriction plates placed symmetrically, normal to the flow, are examined in a small tilting channel. The flow rate  $Q$  is related to the upstream depth  $y_1$  by means of a discharge equation  $Q = Cby_1^{3/2}$ , where  $b$  is the width of opening and  $C$  is an experimental coefficient which depends upon the constriction ratio and the Froude number of the unstricted flow. The values of  $C$  are established for Froude numbers up to 2.1 and constriction ratios up to 95%.

The conditions under which insertion of constriction plates produces an increase in upstream depth are investigated and the extent of the increase is evaluated. (From author's summary)





## III. SUBMERGENCE

BENJAMIN, T. B., On the flow in channels when rigid obstacles are placed in the stream. *J. Fluid Mech.* 1, 2, 227-243. July 56 (AMR 11-503)

Author uses three physical quantities  $Q$ ,  $R$ ,  $S$  introduced in a previous paper (see Benjamin, T. B., and Lighthill, "On cnoidal waves and bores", *Proc. roy. Soc. (A)*, 224, 448-460, 1954) with the meaning

$$Q = vh, \quad R = \frac{1}{2} v^2 h, \quad S = v^2 h + \frac{1}{2} gh^2$$

i.e.,  $Q$  is the flow rate,  $R$  the energy for unit mass, and  $S$  the momentum flow rate for unit span (corrected for changes in horizontal pressure force due to changes in depth) and divided by density. Invariability of these quantities at different cross sections implies, respectively, conservation of flow rate, of energy, and of momentum.

This present paper is divided in five parts: 1-Introduction; 2-General theory of flow; 3-Flow under a sluice-gate; 4-Flow under a planning surface; 5-Experimental tests.

Parts 1 and 2 deal with some properties of flow and waves. In the last three parts, author studies the flow under a vertical or inclined gate. This subject has also been treated in the Italian papers of Gentilini *Energia elett.* April and June 1941 and March *Ann. Mat. pura appl.* (IV) 34, 1953.

BINNIE, A.M., The flow of water under a sluice-gate. *Quart. J. Mechn. appl. Math* 5, Part 4, 395-407, Dec. 1952. (AMR 6-2256.)

By introducing the Froude number of the flow, author simplifies relationship between conditions upstream and downstream of sluice gate. Well-known expressions are derived for alternate depth of flow, discharge, and force in the gate. A simple explanation is presented for the absence of waves on both sides of the gate. Coefficient of contraction  $C_c$  of the issuing flow is given as a review of experimental and theoretical investigations. Actually, author does not mention  $C_c$ , but presents instead the gate opening required to produce given Froude number.

BIRKHOFF, G. Calculation of Potential Flow with Free Streamlines. *ASCE Jour. Hydr. Div.* Vol. 87-HY6. Nov., 1961.

The most recent survey of the methods for computing three classes of steady potential flows with free streamlines: (1) plane flows having free boundaries and curved fixed boundaries without gravity; (2) plane flows having free boundaries and straight fixed boundaries with gravity and (3) axially symmetric flow having free boundaries without gravity.

Discussion by H. Rouse (March 1962, p. 187); L. Landweber (May, 1962 p. 223); S. P. Garg, T. S. Strelkoff and Y. S. Yu (July 1962, p. 293), and the closing discussion by G. Birkhoff, (March 1963, p. 147) point out the limitations of the mathematical methods; and comparisons between theoretical calculations and experimental results are given. The paper along with its discussions provides an excellent source of references on the subject.



BLISDELL, F. W. Comparison of Sluice Gate Discharge in Model and Prototype, Trans. ASCE Vol. 102 p. 544. 1937.

"(1) Models of sluice gates can be depended upon to predict the discharge of their prototypes with reasonable accuracy, (2) Froude model law will apply to the discharge of sluice-gate, (3) Roughness of both model and prototype must be given consideration in the construction of the model; and (4) good results should not be expected for small gate-openings and low velocities". (From Authors Conclusion.)

FRANKE, P., Jet contraction in flow under sluice gates in rectangular channels. Bautechnik 32, 8, 257-259, Aug. 55. (AMR 9-2240)

Analytical study is based on energy considerations of the flow under a sluice gate in a rectangular channel. Author computes the downstream depth in the case where energy losses are neglected and in the case where they are taken into consideration. Values of the coefficient of contraction are given for different ratios of upstream depth to gate opening. All results are expressed in dimensionless form.

FRANKE, P., Theoretical consideration of jet contraction in flows under a sluice gate. Bautechnik 33, 3, 73-77, March '56. (AMR 9-3636)

Author analyzes the contraction of an irrotational stream issuing from the opening of a sluicgate. In the first part of the analysis use is made of the results of von Mises (who did not consider gravity) for flow from a two-dimensional opening. The computed results do not compare well with the experimental data given in the paper.

The only exact (in the sense that no assumption in addition to irrotationality is made) solution for the sluice-gate problem is that of Southwell and Vaisey Phil. Trans. (A) 240, 117-161, which yields results in better agreement with author's experimental curve than any of his curves obtained from calculation.

GENTILINI, B., Flow under inclined or radial sluice gates. W.E.S. Translation 51-9; 11 pp., Nov. 1951. (AMR 5-1441)

Theoretical and experimental determinations were made of coefficient of discharge for inclined and radial sluice gates. Experimental channel was 16 cm wide, and angles of inclination of 15°, 30°, 45°, 60°, 75° and 90° were used. Opening ranged from 3 cm to 9 cm. Results closely checked theoretical coefficients that were derived from the specific energy relation.

ROUSE, H., and ABUL-FETOUH, A. H., Characteristics of irrotational flow through axially symmetric orifices. J. Appl. Mech. 17, 4, 421-426, Dec. 1950 (AMR 4-3279.)

Although an exact analytical solution of the orifice problem has not yet proved feasible, use of the relaxation method has permitted a numerical determination of flow characteristics to be made with sufficient precision for the problem to be considered solved. The coefficient of contraction is found to be practically identical with that evaluated by von Mises for two-dimensional flow from





slots over the entire range of area ratio, and reasonable agreement is shown to exist between measurement and computation. Coordinates of the jet profiles are presented in tabular and graphical form, and are found to differ appreciably from those previously adapted from the two-dimensional case. A composite dimensionless chart is also provided showing the distribution of pressure along the boundary and center line and across the efflux section for the various area ratios. (From authors summary.)





## CHAPTER III THEORETICAL ANALYSIS

III-1 Flow Configuration at an Open Channel Constriction

The backwater due to a constriction in an open channel depends mainly on the boundary geometry, the discharge and the regime of the flow, i.e., the Froude Number. The phenomenon is usually so complicated that the resulting flow pattern is not entirely subject to analytical solution. A practical solution is only possible through experiments.

In the natural streams, the Froude Number of the flow usually ranged from 0.1 to 0.5. In this range of Froude Numbers the constriction will induce a pronounced backwater effect that extends a long distance upstream. A critical control section may exist at the constriction. When a critical control section exists at the constriction, a hydraulic jump occurs downstream of the constriction.

When a constriction is introduced into an otherwise uniform, friction-controlled flow in a prismatic channel of mild slope (see Fig. 3-1), a backwater of the M-1 type is developed upstream of the constriction. Upstream of the backwater curve the flow is undisturbed and the flow distribution is governed by the channel characteristics. Approaching the constriction, the flow decelerates as the depth increases. The deceleration process continues until a section (designated section (1)) is reached. Farther downstream the flow begins to accelerate owing to the convergence of the flow into the contracted opening (section 2). The flow pattern between sections 1 and 2 is essentially dominated by the constriction geometry.

As the fluid passes through the opening, the live stream contracts to a width somewhat less than that of the opening and the corresponding average longitudinal profile drops sharply. At the section of minimum (section 3) the expansion process begins and continues until normal flow again is established at some distance downstream (section 4).



The boundary roughness plays an important role in the downstream pattern of motion, especially when the flow just downstream of the constriction becomes supercritical. The roughness may force the hydraulic jumps to move upstream, and may eventually reach the downstream face of the constriction.

When the constriction is submerged, the centerline profile and plan view are as shown in figures 3-2 and 3-3 respectively. In figure 3-2 the approaching water surface is shown to have a profile of an  $M_1$  curve;  $Y_0$  or  $Y_n$  is the normal depth of the unobstructed channel flow,  $Y_1$  is the depth at the section of maximum backwater,  $Y_2$  is the downstream depth taken in the deadwater flow portion of the channel, and  $Y_3$  is the depth of the live stream at the vena contracta. The flow may be fully submerged as shown by the solid line or the discharge may be free at the downstream end of the constriction. The plan view of the channel constriction flow in figure 3-3 shows the streamlines of the flow entering the opening. The velocity upstream of the constriction is low and the streamlines follow the walls very closely. The eddies sketched on the upstream side of the opening moves in a vertical plane in a screw motion towards the opening. A particle in the corner would not remain in this region but due to these eddies it moves towards the opening. The eddies downstream of the constriction, shown on both sides of the jet, are in the horizontal plane and are less active. Particles could often remain there for longer periods of time.





The three basic equations of fluid mechanics: conservation of mass, conservation of momentum, and conservation of energy are used in the following study. These are applied to a definite volume called the control volume (c.v.) and the boundary of this volume is known as the control surface (c.s.). The shape of the control volume remains constant, but the amount and identity of the fluid in it may vary in time.

The flow configurations in the problem at hand are strictly three-dimensional. However, in order to simplify the analysis, a one-dimensional flow in which the velocity and the depth of flow vary only along the path of the channel is often used. In addition, the flow is that of a real fluid, that is to say that friction is present; boundary layers exist and flow separation may occur. The flow is thus rotational. The rotationality of the flow and its three-dimensional characteristics preclude the use of potential flow theory. The free streamline theory, so ably reviewed by Birkhoff<sup>(1)</sup> (1961) is not applicable.

The errors introduced by using a one-dimensional analysis may be eliminated by using suitable correction coefficients. However, in practice these coefficients are not known exactly, and even in the laboratory, their evaluation requires time-consuming measurements and calculations. It is, therefore, often customary to use the one-dimensional analysis without correction factors, realizing the limitations of such an analysis. The approximations so-obtained are nevertheless useful for engineering design; their accuracy is consistent with that of the data of the problem. It must be recognized that in the design of a bridge waterway opening, the design flow obtained from hydrologic computation is seldom known exactly and errors of  $\pm 20\%$  are common. Furthermore, all the irregularities of a natural water course cannot be taken into consideration, and average values or typical cross sections of the stream are considered. In the reverse problem of calculating a flood discharge from high water marks, the several inaccuracies inherent to the high water mark measurement and changes in roughness coefficient at high stages make it difficult to

The three basic equations of fluid mechanics, conservation of mass, conservation of momentum, and conservation of energy, are used in the following manner. The continuity equation is applied to a definite volume called the control volume (Fig. 1). The mass flow rate is known as the control surface (Fig. 1). The mass flow rate is known as the control surface (Fig. 1). The mass flow rate is known as the control surface (Fig. 1).

The flow configuration in the problem is defined by the geometry of the flow domain. In order to obtain a solution, the flow domain is divided into a finite number of elements. The elements are defined by the geometry of the flow domain. The elements are defined by the geometry of the flow domain. The elements are defined by the geometry of the flow domain. The elements are defined by the geometry of the flow domain.

The errors introduced by the use of a finite number of elements are of two types: truncation errors and round-off errors. Truncation errors are caused by the use of a finite number of elements. Round-off errors are caused by the use of a finite number of elements. The errors introduced by the use of a finite number of elements are of two types: truncation errors and round-off errors. Truncation errors are caused by the use of a finite number of elements. Round-off errors are caused by the use of a finite number of elements.

It must be recognized that in the design of a hydraulic structure, the flow obtained from hydraulic computation is seldom known exactly and errors are common. Furthermore, all the irregularities of a natural water course must be taken into consideration, and average values or typical cross sections of the stream are considered. In the reverse problem of calculating a flood discharge from high water marks, the several uncertainties inherent in the data must be taken into account, and changes in roughness coefficients at high stages must be considered.

evaluate the discharge closer than within 10 to 15%.

The conservation of mass is expressed by the continuity equation which for a steady incompressible flow takes the form

$$\oint_{C.S.} \vec{V} \cdot d\vec{A} = 0 \quad (3-2-1)$$

in which the integral of the net efflux is taken around the whole control surface (C.S.). This equation simply states the inflow into the control volume (C.V.) is equal to the outflow from the control volume, and its one-dimensional form takes the usual form

$$V_1 A_1 = V_2 A_2 \quad (3-2-2)$$

The conservation of momentum for steady flow states that the sum of the external forces on the control surface and of the body forces (usually gravity) acting inside the control volume is equal to the net rate of efflux of momentum across the control surface:

$$\vec{F}_s + \iiint_{C.V.} \vec{B} \rho \, dV = \iint_{C.S.} \vec{V} (\rho \vec{V} \cdot d\vec{A}) \quad (3-2-3)$$

where  $\vec{F}_s$  represents the external surface forces and  $B$  is the body force per unit of mass. The one dimensional counterpart of this equation is

$$F_x = \rho Q (\beta_2 V_{x2} - \beta_1 V_{x1}) \quad (3-2-4)$$

where  $\beta$  is the momentum correction factor which takes into account the non-uniformity of the velocity distribution

$$\beta = \frac{1}{A} \iint (u/V)^2 \, dA \quad (3-2-5)$$

The momentum equation applied to a straight open channel reach is:

$$\rho Q (\beta_2 V_2 - \beta_1 V_1) = P_1 - P_2 + W \sin \theta - F_f \quad (3-2-6)$$

where  $P_1$  and  $P_2$  are the resultant forces acting on the end sections of the reach



estimate the discharge chosen from which is as follows:

The summation of mass is determined by the continuity equation and is

steady incompressible flow then the mass

$$\rho \int_V \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_1} \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_2} \mathbf{v} \cdot d\mathbf{V}$$

in which the integral of the velocity over the volume is the same for any two volumes

This equation is very useful in the analysis of fluid flow in a pipe or channel

continuity from the known velocity profile at one section to the velocity profile at another

$$\rho \int_V \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_1} \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_2} \mathbf{v} \cdot d\mathbf{V}$$

The continuity equation is a statement of the conservation of mass

for a fluid element in a steady flow field, it states that the mass entering the element

the control volume is equal to the mass leaving the control volume

equation

$$\rho \int_{V_1} \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_2} \mathbf{v} \cdot d\mathbf{V}$$

where  $\rho$  is the density of the fluid and  $\mathbf{v}$  is the velocity vector

mass. The mass distributed over the volume of the control volume is

$$\rho \int_V \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_1} \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_2} \mathbf{v} \cdot d\mathbf{V}$$

where  $\rho$  is the mass per unit volume and  $\mathbf{v}$  is the velocity vector

of the velocity distribution

$$\rho \int_V \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_1} \mathbf{v} \cdot d\mathbf{V} = \rho \int_{V_2} \mathbf{v} \cdot d\mathbf{V}$$

(1-2-3)

The momentum equation applied to a straight open channel flow is

$$\rho Q (V_2 - V_1) = P_1 A_1 - P_2 A_2 + W \sin \theta - F_f$$

where  $P_1$  and  $P_2$  are the resultant forces acting on the end sections of the control

$W$  is the weight of water between the sections

$\theta$  is the angle of inclination of the channel

$F_f$  is the external friction force exerted by the boundaries on the fluid

The friction force  $F_f$  may be evaluated from Manning's formula written for the boundary shear stress

$$\tau_o = \frac{14.5 n^2 \rho V^2}{R^{1/3}} \quad (3-2-7)$$

where  $\tau_o$  is the average boundary shear and  $R$  is the hydraulic radius.

The specific force equation is obtained by applying the momentum equation to a short prismatic horizontal open channel reach, neglecting the friction force and assuming a hydrostatic pressure distribution:

$$\beta_1 \frac{Q^2}{gA_1} + \bar{Y}_1 A_1 = \beta_2 \frac{Q^2}{gA_2} + \bar{Y}_2 A_2 \quad (3-2-8)$$

or

$$F_{s1} = F_{s2}$$

where  $F_s$  is the specific force, and where  $\bar{Y}$  is the head over the center of gravity of the cross section.

The conservation of energy for steady flow may be written

$$\oint_{C.S.} (V^2/2g + Z + p/\gamma) (\vec{V} \cdot d\vec{A}) = \text{hydraulic losses} \quad (3-2-9)$$

and its one dimensional counterpart is

$$\alpha_1 V_1^2/2g + Z_1 + p_1/\gamma = \alpha_2 V_2^2/2g + Z_2 + p_2/\gamma + h_f \quad (3-2-10)$$

where  $\alpha$  is the energy correction factor which takes into account the non-uniformity of the velocity distribution

$$\alpha = 1/A \iint (u/V)^3 dA \quad (3-2-11)$$



The head loss in steady uniform flow in open channel flow may be evaluated from

Manning's formula

$$V = (1.486/n) R^{2/3} S^{1/2} \quad (3-2-12)$$

where

$$S = h_f/L \quad (3-2-13)$$

is the head loss per unit length.

In open channel flow, it is convenient to consider the energy with respect to the bottom as a datum. This is the specific energy first introduced by Bakhmeteff<sup>(2)</sup>:

$$E = V^2/2g + Y \quad (3-2-14)$$

In this form it is assumed that the velocity is uniform and that the streamlines are essentially parallel, thus the pressure is hydrostatic. If the velocity is not uniform, and if the streamlines are curved, the velocity head is multiplied by the kinetic energy coefficient, and the depth  $y$  may be multiplied by a pressure coefficient ( $\alpha'$ )

$$\alpha' = 1 + 1/Qy \iint c V dA \quad (3-2-15)$$

where

$$c = (d/g) V^2/r \quad (3-2-16)$$

and is positive for concave flow and negative for convex flow,  $d$  being the depth, and  $r$  the radius of curvature of a streamline. The specific energy thus becomes in general

$$E = \alpha V^2/2g + \alpha' Y \quad (3-2-17)$$

The specific force and the specific energy equations are used to define a number of open channel flow characteristics. When the specific energy or the specific force is minimum, the flow is called critical. The following relationship for critical flow may be derived from the specific energy equation for a stream of an arbitrary cross section, with  $\alpha' = 1$





$$Q^2/g = A_c^3/W_c \quad (3-2-18)$$

$$Q/\sqrt{g/\kappa} = Z; \quad Z = A\sqrt{A/W} = A\sqrt{D} \quad (3-2-19)$$

$$\kappa V^2/2g = A_c/2W_c = D_c/2 \quad (3-2-20)$$

$$V = \sqrt{(g/\kappa) (A_c/W_c)} = \sqrt{g D_c/\kappa} \quad (3-2-21)$$

$$V/\sqrt{g D_c/\kappa} = F = 1 \quad (3-2-22)$$

where  $W$  is the width of the free surface,  $Z$  is the section factor for critical flow computation,  $D$  is the hydraulic depth, and  $F$  is the Froude number. For a stream of rectangular cross section, letting  $q$  be the discharge per unit width, the above relationships take the following simplified forms:

$$q = [g y_c^3/\kappa]^{1/2} \quad (3-2-23)$$

$$\kappa V^2/2g = y_c/2 \quad (3-2-24)$$

$$V_c = [g y_c/\kappa]^{1/2} \quad (3-2-25)$$

$$y_c = [\kappa q^2/g]^{1/3} \quad (3-2-26)$$

$$E = 3/2 y_c \quad (3-2-27)$$

For flow in rectangular channels the specific force and the specific energy equations may be written in a dimensionless form, making use of the critical flow relationships. They are respectively

$$\frac{\bar{Y}_1}{Y_1} \left[ \frac{Y_1}{Y_c} \right]^2 + \beta_1 \frac{Y_2}{Y_1} = \frac{\bar{Y}_2}{Y_2} \left[ \frac{Y_2}{Y_c} \right]^2 + \beta_2 \frac{Y_2}{Y_2} \quad (3-2-28)$$

and

$$\frac{Y_1}{Y_c} + \alpha_1 \left( \frac{Y_c}{Y_1} \right)^2 = \frac{Y_2}{Y_c} + \alpha_2 \frac{Y_c}{Y_2}^2 \quad (3-2-29)$$

where the ratio  $\bar{Y}/Y$  is a geometric characteristic of the cross section and is equal to 0.5 for rectangular channels,  $y$  being the head over the center of gravity of the section.



### III-3 Types of Flow at a Bridge Constriction

Six classes of flow may exist at a bridge constriction:

Class 1 - The flow is subcritical throughout the transition

Class 2 - The flow passes from subcritical to supercritical in the transition

Class 3 - The flow is supercritical throughout the transition

Class 4 - The flow passes from supercritical to subcritical near the transition

Class 5 - The transition inlet is submerged but the outlet is free, resulting in a free orifice flow.

Class 6 - The transition inlet and outlet are submerged resulting in a submerged orifice flow.

The following analysis illustrates a method of distinguishing between the first four types of free surface flow. The latter two types are not truly free surface flow. A method to discriminate between the free surface flow and the orifice flow is also given.

As the flow towards the constriction is an accelerating flow, and as the energy losses are relatively small in a converging flow, the energy equation is suitable to describe the flow between sections 1 and 3. The expanding flow between sections 3 and 4 is better described by a momentum equation.

The first four types of flow may be delineated by the following simplified analysis. Writing an energy equation between sections 1 and 2,

$$\alpha_1 \frac{V_1^2}{2g} + \alpha'_1 Y_1 = \alpha_3 \frac{V_3^2}{2g} + \alpha'_3 Y_3 + h_f \quad (3-3-1)$$

Assuming  $\alpha_1 = \alpha_3 = \alpha'_1 = \alpha'_3 = 1$  and  $h_f = 0$ , letting  $b_3$  the mean width of the stream at section 3, making use of the continuity equation

$$V_1 BY_1 = V_3 b_3 Y_3$$

the equation of energy may be re-written, after dividing both sides by  $Y_1$ .





$$\frac{V_1^2}{2gY_1} + 1 = \frac{V_1^2}{2gY_1} \left( \frac{B}{b_3} \frac{Y_1}{Y_3} \right)^2 + \frac{Y_3}{Y_1} \quad (3-3-2)$$

or

$$\frac{1}{2} F_1^2 \left[ \left( \frac{B}{b_3} \frac{Y_1}{Y_3} \right)^2 - 1 \right] = 1 - \frac{Y_3}{Y_1} \quad (3-3-3)$$

or

$$F_1^2 = \frac{2 \left( 1 - \frac{Y_3}{Y_1} \right)}{\left( \frac{B}{b_3} \frac{Y_1}{Y_3} \right)^2 - 1} \quad (3-3-4)$$

$$= \frac{2 \left( \frac{Y_3}{Y_1} \right)^2 \left( 1 - \frac{Y_3}{Y_1} \right)}{\left( \frac{B}{b_3} \right)^2 - \left( \frac{Y_3}{Y_1} \right)^2} \quad (3-3-5)$$

$F_1$  is plotted as a function of  $\frac{Y_3}{Y_1}$  in terms of  $\frac{B}{b_3}$  in Fig. 3-2. The curve for which the flow is critical at section 3 corresponds to  $F_3 = 1$ , and is obtained from the continuity equation:

$$V_1 B Y_1 = V_3 b_3 Y_3 \quad (3-3-6)$$

or

$$V_1^2 B^2 Y_1^2 = V_3^2 b_3^2 Y_3^2 \quad (3-3-7)$$

or

$$\frac{V_1^2}{gY_1} \cdot \frac{B^2}{b_3^2} \cdot \frac{Y_1^3}{Y_3^3} = \frac{V_3^2}{gY_3} \quad (3-3-8)$$

or

$$F_1^2 \cdot \frac{B^2}{b_3^2} \cdot \frac{Y_1^3}{Y_3^3} = F_3^2 \quad (3-3-9)$$

When the flow is critical at section 3,  $F_3 = 1$  and

$$F_1^2 = \left( \frac{Y_3}{Y_1} \right)^3 \left( \frac{b_3}{B} \right)^2 \quad (3-3-10)$$

Solving the two equations simultaneously:

$$F_1^2 = \frac{2 \left( \frac{Y_3}{Y_1} \right)^2 \left( 1 - \frac{Y_3}{Y_1} \right)}{F_1^2 \left( \frac{Y_3}{Y_1} \right)^3 - \left( \frac{Y_3}{Y_1} \right)^2} \quad (3-3-11)$$



or

$$F_1^4 - F_1^2 \left(\frac{Y_2}{Y_1}\right)^5 - 2 \left(\frac{Y_2}{Y_1}\right)^5 \left(1 - \frac{Y_2}{Y_1}\right) = 0 \quad (3-3-12)$$

from which

$$2 F_1^2 = \left(\frac{Y_2}{Y_1}\right)^5 \pm \sqrt{\left(\frac{Y_2}{Y_1}\right)^{10} + \left(\frac{Y_2}{Y_1}\right)^5 \left(1 - \frac{Y_2}{Y_1}\right)} \quad (3-3-13)$$

Only the positive sign in front of the square root has a physical significance.

This equation gives the values of the Froude number at section 1 corresponding to a Froude number of unity at the vena contracta.

The plane of Fig. 3-2 is thus divided in 4 regions:

Above the line  $F_1 = 1.0$  the flow is supercritical in the approach of the constriction, below the line  $F_1 = 1.0$ , the flow is subcritical at section 1. Above the curve  $F_2 = 1$ , the flow is supercritical, and below the curve  $F_2 = 1$  the flow is subcritical. The four regions of the figure are labelled according to the four classes of flow listed at the beginning of this section.





### III-4. Discrimination Between Free Surface Flow and Orifice Flow

Orifice flow will occur when the head over the crown of the arch exceeds the velocity head plus the head loss in the orifice.

Thus for the limiting case, calling  $r$  the semi-circular arch radius:

$$\frac{V_3^2}{2g} + \left( \frac{1}{C_v^2} - 1 \right) \frac{V_3^2}{2g} = Y_1 - r \quad (3-4-1)$$

where  $\left( \frac{1}{C_v^2} - 1 \right) \frac{V_3^2}{2g}$  is the orifice head loss.

$$\text{Then} \quad \frac{1}{C_v^2} \frac{V_3^2}{2g} = Y_1 - r \quad (3-4-2)$$

By continuity  $V_1 B Y_1 = V_3 b_3 Y_3 = V_3 C_o A_o$  where  $A_o$  is the opening area.

$$\text{Then} \quad \frac{1}{C_v^2} \frac{V_1^2}{2g} \frac{B^2 Y_1^2}{C_o^2 A_o^2} = Y_1 - r \quad (3-4-3)$$

$$\frac{V_1^2}{2g Y_1} = \left( 1 - \frac{r}{Y_1} \right) C_d^2 \left( \frac{A_o}{A_1} \right)^2 \quad (3-4-4)$$

$$F_1^2 = 2 C_d^2 \left( 1 - \frac{r}{Y_1} \right) \left( \frac{A_o}{A_1} \right)^2 \quad (3-4-5)$$

There will be submergence when

$$F_1^2 < 2 C_d^2 \left( 1 - \frac{r}{Y_1} \right) \left( \frac{A_o}{A_1} \right)^2 \quad (3-4-6)$$

where  $C_d \approx 0.55$ .

$$\text{or when} \quad F_1^2 < 1/8 C_d^2 \pi^2 \left( 1 - \frac{1}{2} \frac{b}{Y_1} \right) \left( \frac{b}{B} \right)^2 \left( \frac{b}{Y_1} \right)^2 \quad (3-4-7)$$

and since  $\frac{b}{B} = M$

$$\text{when} \quad \frac{F_1^2}{M^2} < 1/8 \pi^2 C_d^2 \left( 1 - \frac{1}{2} \frac{b}{Y_1} \right) \left( \frac{b}{Y_1} \right)^2 \quad (3-4-8)$$



An empirical relationship to distinguish between free surface flow and orifice flow, can be obtained, making use of the notation developed in the article on dimensional analysis, and of the results of chapter 5.

From free surface flow experiments (see chapter 5)

$$\frac{Y_1}{Y_n} = 1 + 0.47 \left( \frac{F_n}{M^0} \right)^{2.26} = 1 + 0.47 \frac{1}{C_m^{2.26}} \left( \frac{F_n}{M} \right)^{2.26} \quad (3-4-9)$$

where  $C_m = M^0/M$ . (See Figure 3-12)

From orific flow experiments (see chapter 5)

$$\frac{Y_1}{Y_n} = 1 + 1.18 \left[ \frac{\frac{F_n}{A_0}}{\frac{B}{Y_n}} \right]^{1.8} = 1 + 1.18 \left( \frac{g}{H} \right)^{1.8} \left[ \frac{Y_n}{b} \right]^{1.8} \left[ \frac{F_n}{M} \right]^{1.8} \quad (3-4-10)$$

Equating  $\left[ \frac{F_n}{M} \right]^{0.46} = 13.46 \quad C_m^{2.26} \left( \frac{Y_n}{b} \right)^{1.8} \quad (3-4-11)$

and since for  $d = 0$

$$C_m = \frac{1}{2} \left\{ \sqrt{1 - \left( \frac{Y_n}{r} \right)^2} + \frac{r}{Y_n} \sin^{-1} \frac{Y_n}{r} \right\} \quad (3-4-12)$$

For the limiting case

$$\left( \frac{F_n}{M} \right)^{0.46} = 13.46 \left\{ \frac{1}{2} \sqrt{1 - \left( \frac{Y_n}{r} \right)^2} + \frac{r}{Y_n} \sin^{-1} \frac{Y_n}{r} \right\}^{2.26} \left( \frac{Y_n}{2r} \right)^{1.8} \quad (3-4-13)$$

A plot of this relationship is given in figure 3-5, from which it is possible to predict for a given Froude, normal depth and contraction geometry, whether the flow will be free or submerged.





### III-5 Flow Class 1 - Subcritical Flow through Unsubmerged Constriction

#### a) General considerations

This is the most common case. The flow pattern divides itself in two parts: (see fig. 3-1).

- 1) a zone of contracting or accelerating flow, from the section of maximum backwater (section 1) to the section of minimum area or "vena contracta" - (section 3).
- 2) a zone of expanding or decelerating flow, from the vena contracta (section 3) to the section where the stream has regained its normal depth (section 4).

It is, therefore, expected that the analysis of the flow pattern would be divided in two parts. An energy equation may be used for the analysis of the contracting flow, and a momentum equation for that of the expanding flow. Section 4, at which the flow occurs at normal depth is the control section. The calculation of the flow profile for a given discharge could proceed from section 4 to section 3 by means of the momentum equation, and from section 3 to section 1 by means of the energy equation, the continuity equation being used to relate the areas at the several sections. The difficulty in this approach lies in the lack of proper definition of the geometry of section 3. The geometry of section 2, at the section of separation, is defined by the water depth, as the geometry of the constriction is assumed to be known -- in our case a semi-circular arch.

At section 2 the flow separates from the solid boundaries, and the three-dimensional live stream converges to the vena contracta. The geometry of the free boundary of the convergent live stream cannot be determined by means of the free streamline theory as the latter is limited to two-dimensional flow. Consequently, it is customary to make some assumption on the flow geometry between sections 2 and 3. Typical assumptions are:

- a) The geometry of section 3 is assumed.
- b) The depths at sections 2 and 3 are assumed to be identical.
- c) The depth at section 2 is assumed to be equal to the normal depth of the

# 1. General introduction

This is the first section of the book. It contains the following

(see Fig. 1-1)

1. A brief introduction to the subject of the book.

2. A brief introduction to the subject of the book.

3. A brief introduction to the subject of the book.

4. A brief introduction to the subject of the book.

5. A brief introduction to the subject of the book.

6. A brief introduction to the subject of the book.

7. A brief introduction to the subject of the book.

8. A brief introduction to the subject of the book.

9. A brief introduction to the subject of the book.

10. A brief introduction to the subject of the book.

11. A brief introduction to the subject of the book.

12. A brief introduction to the subject of the book.

13. A brief introduction to the subject of the book.

14. A brief introduction to the subject of the book.

15. A brief introduction to the subject of the book.

16. A brief introduction to the subject of the book.

17. A brief introduction to the subject of the book.

18. A brief introduction to the subject of the book.

19. A brief introduction to the subject of the book.

20. A brief introduction to the subject of the book.

21. A brief introduction to the subject of the book.

22. A brief introduction to the subject of the book.

23. A brief introduction to the subject of the book.

24. A brief introduction to the subject of the book.

25. A brief introduction to the subject of the book.

uncontracted stream.

The three assumptions will be discussed.

a) Assumed geometry at section 3.

Experiments by P. F. Biery indicate (Fig. 7-2-7) that the depth at section 3 is not uniform across the section, but that in the dead water region it is only 1% larger than across the live stream. The depth  $Y_3$  may thus be reasonably assumed constant across the section. The width of the live stream  $b_3$  may be approximated using the two-dimensional coefficient of contraction and

$$b_3 = C_{c2} b \quad (3-4-1)$$

Thus the cross section of the livestream would be

$$A_3 = C_{c2} b Y_3 \quad (3-5-2)$$

The values of the coefficients of contraction for slots, after von Mises<sup>(2)</sup> is given in the following table:

$\frac{b}{B}$	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$C_{c2}$	0.611	0.612	0.616	0.622	0.631	0.644	0.662	0.687	0.722	0.761	1.00

This assumption makes it possible to relate the depth  $Y_n = Y_1$  to  $Y_3$  by means of the momentum equation, and then  $Y_3$  to  $Y_1$  by means of the energy equation.

b) Assumed equality of depths at sections 2 and 3.

This assumption was used by Tracy and Carter (ASCE Trans. 1955 p. 997). The experiments of P. F. Biery, (Jour. Hyd. Div. ASCE, Vol. 88 No. HY2 p. 96, Fig. 13) do not substantiate this assumption.

c) Depth at section 2 assumed equal to normal depth of uncontracted stream.

This assumption has been implied by Izzard (ASCE Trans 1955, p. 1010). Although this assumption cannot be justified theoretically, the experiments of P. F. Biery show that this assumption is approximately satisfied. It is then possible to express the head loss in the constriction as a function of the velocity head at section 2,



The three assumptions will be discussed.

a) Assumed velocity at section 1

Experiments by P. F. Blissy indicate (Fig. 7-3-7) that the depth at section 1 is not uniform across the section, but that in the dead water region it is larger than across the live stream. The depth  $Y_1$  may thus be reasonably assumed constant across the section. The width of the live stream  $b_1$  may be assumed using the two-dimensional coefficient of contraction and

$$b_1 = C_{c1} b$$

Thus the cross section of the live stream would be

$$A_1 = C_{c1} b Y_1$$

The values of the coefficients of contraction for sharp cornered orifices are given in the following table:

0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.611	0.612	0.613	0.615	0.622	0.631	0.644	0.662	0.687	0.745	0.815

This assumption makes it possible to relate the depth  $Y_1$  to  $Y$ , to  $Y_2$ , and to  $Y_3$  by means of the momentum equation, and then  $Y_1$  to  $Y_2$  by means of the continuity equation.

b) Assumed equality of depths at sections 2 and 3

This assumption was used by Tracy and Carter (ASCE Trans. 1952, 77, 1010) in their experiments of P. F. Blissy (Ibid. Div. ASCE, Vol. 88, No. 10, 1954, p. 1010). It is not substantiated this assumption.

c) Depth at section 2 assumed equal to normal depth of unobstructed stream

This assumption has been invalid by Issaid (ASCE Trans. 1955, 80, 1010). This assumption cannot be justified theoretically, the experiments of P. F. Blissy show that this assumption is approximately satisfied. It is then possible to assume the head loss in the contraction as a function of the velocity head at section 1.

$$hf = K \frac{Vn^2}{2g} \quad (3-5-3)$$

The depth of flow at section 1 may then be obtained by means of an energy equation between sections 1 and 2 or between sections 1 and 4. This assumption has also been used with reasonable success by I. P. Wu<sup>(4)</sup> in a preliminary calculation of indirect determination of flood discharge from contracted bridge openings and high water marks.

b) Momentum equation for diverging flow

The momentum equation is written between sections 3 and 4 with the assumption that the pressure distribution is hydrostatic at  $x$ . These sections:

$$F_3 + M_3 = F_4 + M_4 + F_D - F_G \quad (3-5-4)$$

$F_3$  and  $F_4$  represent the hydrostatic forces at section 3 and 4 respectively;  $M_3$  and  $M_4$  are the momenta,  $F_D$  is the drag force of the expanding stream on the bottom and  $F_G$  is the component of the gravity force in the direction of the flow.

To calculate the hydrostatic force at sections 3 and 4, let  $Y_3$  and  $Y_4$  be the heads over the respective centers of gravity of the cross sections. To calculate the momentum flux through section 3 it is necessary to evaluate the cross sectional area of the live stream at section 3. It is assumed that

$$A_3 = b_3 Y_3 \quad (3-5-5)$$

The momentum equation may then be written

$$\rho Y_3 b Y_3 + \rho Q V_3 = \rho Y_4 b Y_4 + \rho Q V_4 + F_D - F_G \quad (3-5-6)$$

Making use of the continuity equation, it follows that

$$\rho Y_3 b Y_3 + \rho \frac{Q}{A_3} = \rho Y_4 b Y_4 + \rho \frac{Q}{A_4} + F_D - F_G \quad (3-5-7)$$



or

$$\bar{Y}_3 Y_3 + \frac{q^2 B^3}{8A_3^3} = \bar{Y}_4 Y_4 + \frac{q^2 B^3}{8A_4^3} + \frac{F_D - F_G}{\gamma B} \quad (3-5-8)$$

Introducing the critical depth  $Y_c^3 = q^2/g$ ,

$$\bar{Y}_3 Y_3 + \frac{Y_c^3 B}{Y_3 b_3} = \bar{Y}_4 Y_4 + \frac{Y_c^3}{Y_4} + \frac{F_D - F_G}{\gamma B} \quad (3-5-9)$$

The momentum equation may be written in a dimensionless form by dividing both sides of the above equation by  $Y_c^2$ :

$$\frac{\bar{Y}_3}{Y_3} \left( \frac{Y_3}{Y_c} \right)^2 + \frac{Y_c}{Y_3} \frac{B}{b_3} = \frac{\bar{Y}_4}{Y_4} \left( \frac{Y_4}{Y_c} \right)^2 + \frac{Y_c}{Y_4} + \frac{F_D - F_G}{\gamma B Y_c^2} \quad (3-5-10)$$

The quantity  $\frac{\bar{Y}}{Y}$  is a geometric constant for many cross sections. For example for a

rectangular section

$$\frac{\bar{Y}}{Y} = 0.5$$

triangular section

$$= 0.333$$

semi-circle section

$$= 1 - (4/3)\pi$$

parabola section

$$= 3/5$$

Let  $\frac{\bar{Y}}{Y} = G$  a geometric constant of the section. Then the dimensionless momentum equation becomes:

$$G_3 \left( \frac{Y_3}{Y_c} \right)^2 + \frac{B}{b_3} \frac{Y_c}{Y_3} = G_4 \left( \frac{Y_4}{Y_c} \right)^2 + \frac{Y_c}{Y_4} + \frac{F_D - F_G}{\gamma B Y_c^2} \quad (3-5-11)$$

Neglecting for the time being the contribution of the term

$$(F_D - F_G)/\gamma B Y_c^3$$

and calling the specific force  $F_s$

$$F_s = \gamma \bar{Y} B Y + \rho Q V \quad (3-5-12)$$

then the generalized dimensionless momentum equation becomes:

$$G_x \left( \frac{Y_x}{Y_c} \right)^2 + \frac{B}{b_x} \frac{Y_c}{Y_x} = F_s / \gamma B Y_c^2 \quad (3-5-13)$$





A plot of the relationship is given in the right hand side of figure 3-7, which may be used for an approximate solution of the depth  $Y_3$  if the depth  $Y_4$  is given. The width of the live stream at section 3 is usually unknown a priori, but may be taken as the width of the constriction times a contraction coefficient.

The drag force of the diverging stream on the channel bottom between the vena contracta and section 4 may be obtained by integrating the shear stress over the expansion area along the bottom. From the discussion by Henry<sup>(5)</sup> it appears that the rate of expansion of a submerged jet is approximately 1 on 6. The model is assumed for the zone of expansion is shown Fig. 3-6.

From Manning's formula, the shear stress on the bottom is

$$\tau = \frac{14.5n^2 \rho v^2}{R^{1/3}} = \frac{14.5n^2 \rho Q^2}{Y^{1/3} b'^2 Y^2} = \frac{14.5n^2 \rho Q^2 B^2}{Y^{7/3} b'^2} \quad (3-5-14)$$

and the elementary drag force is

$$dF_D = \tau dA = \frac{14.5n^2 \rho Q^2 B^2}{Y^{7/3} b'} dx \quad (3-5-15)$$

or

$$\frac{dF_D}{Y^{7/3} B Y_c^2} = \frac{14.5n^2 B Y_c}{Y^{7/3} b'} dx = 14.5 \left( \frac{n}{Y_c^{1/6}} \right)^2 \left( \frac{Y_c}{Y} \right)^{7/3} \frac{B}{Y_c} \frac{dx}{b'} \quad (3-5-16)$$

The dimensionless drag force is

$$\frac{F_D}{Y^{7/3} B Y_c^2} = 14.5 \left( \frac{n}{Y_c^{1/6}} \right)^2 \frac{B}{Y_c} \int_0^{L_{3-4}} \left( \frac{Y_c}{Y} \right)^{7/3} \frac{dx}{b'} \quad (3-5-17)$$

Since  $b' = C_d b + x/3$ , and taking an average value of the depth, an approximate value of the drag force is given by

$$\frac{F_D}{Y^{7/3} B Y_c^2} = 14.5 \left( \frac{n}{Y_c^{1/6}} \right)^2 \frac{B}{Y_c} \left( \frac{2Y_c}{Y_n + Y_3} \right) \int_0^{(B-bC_d)} \frac{dx}{4C_d + x/3} \quad (3-5-18)$$

$$= 14.5 \left( \frac{n}{Y_c^{1/6}} \right)^2 \frac{B}{Y_c} \left( \frac{2Y_c}{Y_n + Y_3} \right)^3 \ln \frac{B}{bC_d} \quad (3-5-19)$$



The gravity force is

$$F_G = B \frac{Y_3 + Y_4}{2} L_{3-4} S_0$$

$$= B \frac{Y_3 + Y_4}{2} 3 (B - bC_d) S_0 \quad (3-5-20)$$

and the dimensionless gravity force is

$$\frac{F_G}{BY_c^2} = 3/2 \frac{Y_3 + Y_4}{Y_c} \frac{B - bC_d}{Y_c} S_0 \quad (3-5-21)$$

In the actual computation, a first approximation of  $Y_3$  is obtained by neglecting  $F_D$  and  $F_G$ . With this approximate value of  $Y_3$ , the values of  $F_D$  and  $F_G$  may be calculated from the above equations.

### c) Energy Equation for Converging Flow

The energy equation between sections 1 and 3 may be written:

$$S_1 L_{1-3} + Y_1 + \alpha_1 \frac{V_1^2}{2g} = Y_3 + \alpha_3 \frac{V_3^2}{2g} + h_f \quad (3-5-22)$$

where  $h_f$  is the head loss between sections 1 and 3. Making use of the continuity equation

$$V_1 A_1 = V_3 A_3$$

$$Y_1 + \alpha_1 \frac{q^2}{2gY_1^2} = Y_3 + \alpha_3 \left( \frac{A_1}{A_3} \right)^2 \frac{q^2}{2gY_1^2} + h_f - S_0 L_{1-3} \quad (3-5-23)$$

Introducing the critical depth  $Y_c^3 = q^2/g$

$$\frac{Y_1}{Y_c} + \alpha_1 \left( \frac{Y_c}{Y_1} \right)^2 = \frac{Y_3}{Y_c} + \alpha_3 \left( \frac{B}{b_3} \right)^2 \frac{Y_c}{Y_3} + \frac{h_f}{Y_c} - S_0 \frac{L_{1-3}}{Y_c} \quad (3-5-24)$$

which is the dimensionless form of the energy equation. Assuming  $\alpha_1 = \alpha_3 = 1$ , and neglecting the difference of the last two terms,





$$\frac{Y_1}{Y_c} + \left( \frac{Y_c}{Y_1} \right)^2 = \frac{Y_3}{Y_c} + \left( \frac{B}{b_3} \right)^2 \left( \frac{Y_c}{Y_3} \right)^2 = \frac{E_s}{Y_c} \quad (3-5-25)$$

The plot of this equation is given in the left-hand side of figure 3-7.

The friction loss between sections 1 and 3 may be calculated from the expression

$$h_f = L_{1-2} \frac{Q^2}{K_1 K_3} + L_{2-3} \frac{Q^2}{K_3^2} \quad (3-5-26)$$

The value of the conveyance

$$K = \frac{1.486}{n} AR^{2/3} \quad (3-5-27)$$

may be approximated as follows

$$K_1 = \frac{1.486}{n} BY_1^{5/3} \quad (3-5-28)$$

$$K_3 = \frac{1.486}{n} b_3 Y_3^{5/3} \quad (3-5-29)$$

then

$$\frac{h_f}{Y_c} = \frac{Q^2 B^2 n^2}{(1.486)^2 Y_c} \left\{ \frac{L_{1-2}}{B b Y_1^{5/3} Y_3^{5/3}} + \frac{L_{2-3}}{b_3^2 Y_3^{10/3}} \right\} \quad (3-5-30)$$

$$= \frac{E Y_c^2 n^2 B}{2.2} \left\{ \frac{L_{1-2}}{b} \frac{1}{Y_1^{5/3} Y_3^{5/3}} + \frac{L_{2-3} B}{b_3^2} \frac{1}{Y_3^{10/3}} \right\} \quad (3-5-31)$$

$$= \frac{E}{2.2} \frac{B}{Y_c} \left( \frac{Y_c}{Y_3} \right)^{5/3} \left( \frac{n}{Y_c^{1/6}} \right)^2 \left\{ \frac{L_{1-2}}{b} \left( \frac{Y_c}{Y_1} \right)^{5/3} + \frac{L_{2-3}}{b_3^2} \left( \frac{Y_c}{Y_3} \right)^{5/3} \right\} \quad (3-5-32)$$

The experiments of Biery show that  $L_{1-2} \approx L_{1-3} \approx b$ . Then

$$\frac{h_f}{Y_n} = \frac{E}{2.2} \frac{B}{Y_c} \left( \frac{Y_c}{Y_3} \right)^{5/3} \left( \frac{n}{Y_n^{1/6}} \right)^2 \left\{ \left( \frac{Y_c}{Y_1} \right)^{5/3} + \frac{B b}{b_3^2} \left( \frac{Y_c}{Y_3} \right)^{5/3} \right\} \quad (3-5-33)$$

In an actual computation, a first approximation of  $Y_1$  is obtained by neglecting the difference between the head loss  $h_f$  and  $S_0 L_{1-3}$ . The term neglected is the loss in addition to the normal flow head loss due to the acceleration of the flow between section 1 and 3 and the separation of the flow from the boundaries at section 2. The quantity neglected is usually negligible.



d) Graphical Solution of Backwater due to a Constriction

The dimensionless specific force and specific energy curves may be used to obtain graphically the backwater upstream of a constriction, as was first suggested by H. R. Henry<sup>(6)</sup>. Part of the specific force and specific energy diagram has been enlarged in Fig. 3-8 for the illustration of the graphical method.

As an example, the conditions of the experiment 16-S, Geometry Ia (see table 7-1-2) are illustrated. The data of the problem are:

$$Q = 2.0 \text{ cfs, } Y_n = 20.30 \text{ cm; } M = B/b = 0.491.$$

Calculate

$$Y_c = \left( \frac{Q^2}{gB^2} \right)^{1/3} = 5.24 \text{ cm}$$

and  $Y_n/Y_c = 3.88.$

Enter the diagram with the value of  $Y_n/Y_c = Y_n/Y_c = 3.88$  and proceed to the specific curve labeled  $B/b_3 = 1.0$ , corresponding to no contraction. With a coefficient of contraction  $C_d = 0.64$ , calculate

$$\frac{B}{b_3} = \frac{B}{bC_d} = \frac{1}{MC_d} = \frac{1}{0.491 \times 0.64} = 3.18$$

Proceed on the diagram along a vertical line, corresponding to a constant specific force, until an interpolated curve for  $B/b_3 = 3.18$  is reached. Proceed to the left and read  $Y_3/Y_c = 3.72$ . The experimental value of  $Y_3/Y_c$  was  $\frac{19.41}{3.88} = 5.0$ . With the obtained value of  $Y_3/Y_c$  of 3.72, proceed to an interpolated specific energy corresponding to  $B/b_3 = 3.18$ . Proceed upward following a line of constant specific energy until the curve  $B/b_3 = 1$  is reached, corresponding to no contraction at station 1. Read the value of  $Y_1/Y_c = 4.069$  and calculate  $Y_1 = 4.069 \times 5.24 = 21.30 \text{ cms}$ . The experimental value was 21.26 cms. A good agreement was obtained in spite of the neglect of the friction and head loss terms. However, it should be remembered that the example chosen corresponds to smooth boundaries, and consequently, the head losses are indeed small.





### III-6 Flow Class 2 - The Flow Goes Through Critical in the Constriction

#### a) Geometric Properties of Semi-Circular and Circular Segment Channels

In this type of flow the control is in the constriction, where there exists a relationship between the depth of flow and the discharge. The depth at section 1 may be obtained directly by writing an energy equation between the control section and section 1. As the calculation of the critical depth in a conduit having a semi-circular section, or a circular segment section, is tied to the geometry of the section, this geometry is studied first. At critical stage

$$Z = \frac{Q}{\sqrt{g/\alpha}} \quad (3-6-1)$$

where  $Z = A\sqrt{\bar{y}}$  (3-6-2)

and  $\bar{y}$  is the hydraulic depth, defined by

$$\bar{y} = \frac{A}{W} \quad (3-6-3)$$

where  $W$  is the free surface width.

The geometric properties of the semi-circular and circular segment arches are summarized in Fig. 3-9. The top right hand side quadrant gives the relationship between the section factor for critical flow computation and the critical depth in terms of the distance from the springline to the center of curvature of the arch. The curve labeled  $d/b = 0$  corresponds to the semi-circular arch. In order to obtain the critical depth in the constriction of a given diameter  $b$  for a given discharge  $Q$ , one calculates the section factor for critical flow  $Z$  by means of the relation

$$\frac{Q}{\sqrt{g/\alpha}} = Z$$

and entering the diagram with the proper value of  $Z/b^{5/2}$  for the desired  $d/b$  one reads the ratio of the critical depth to the diameter  $Y_c/b$ . The value of the hydraulic depth  $\bar{y}$  and of the free surface width  $W$  can be obtained by means of the sets of curves in the top and bottom left hand side of the figure respectively.



With reference to Fig. 3-9 (bottom right hand side) the area of the section of depth  $y$  is:

$$A = \frac{b^2}{8} \sec^2 \frac{\theta_2}{2} (\theta_1 - \theta_2 + \sin \theta_1 - \sin \theta_2) \quad (3-6-4)$$

the free surface is

$$W = b \frac{\cos \frac{\theta_1}{2}}{\cos \frac{\theta_2}{2}} \quad (3-6-5)$$

the hydraulic depth is

$$\bar{y} = \frac{A}{W} = \frac{b}{8} \frac{\theta_1 - \theta_2 + \sin \theta_1 - \sin \theta_2}{\cos \frac{\theta_1}{2} \cos \frac{\theta_2}{2}} \quad (3-6-6)$$

the section factor for critical flow computation is:

$$Z = A \sqrt{\bar{y}} = \frac{b^{2/8}}{\cos^2 \frac{\theta_2}{2}} (\theta_1 - \theta_2 + \sin \theta_1 - \sin \theta_2) \sqrt{\frac{b}{8} \frac{\theta_1 - \theta_2 + \sin \theta_1 - \sin \theta_2}{\cos \theta_1 \cos \theta_2}} \quad (3-6-7)$$

or in dimensionless form:

$$Z = \frac{b^{5/2}}{8^{3/2}} \frac{(\theta_1 - \theta_2 + \sin \theta_1 - \sin \theta_2)^{3/2}}{(\cos \frac{\theta_2}{2})^{5/2} (\cos \frac{\theta_1}{2})^{1/2}} \quad (3-6-8)$$

$$\frac{Z}{b^{5/2}} = \frac{1}{8^{3/2}} \frac{(\theta_1 - \theta_2 + \sin \theta_1 - \sin \theta_2)^{3/2}}{(\cos \frac{\theta_2}{2})^{5/2} (\cos \frac{\theta_1}{2})^{1/2}} \quad (3-6-9)$$

The above relationships were used to prepare the curves of Fig. 3-9.

#### b) Limiting Backwater

The purpose of the following analysis is to calculate the backwater at Section 1 when the flow goes through critical in the constriction. This type of flow represents the boundary between classes 1 and 2.



Assuming that the kinetic energy coefficient and the pressure coefficients are unity, the specific energy equation is

$$Y_1 + \frac{V_1^2}{2g} = Y_2 + \frac{V_2^2}{2g} \quad (3-6-10)$$

or 
$$Y_1 \left( 1 + \frac{V_1^2}{2gY_1} \right) = \bar{Y}_2 \left( \frac{Y_2}{Y_1} + \frac{V_2^2}{2g\bar{Y}_2} \right) \quad (3-6-11)$$

or 
$$Y_1 \left( 1 + \frac{F_1^2}{2} \right) = \bar{Y}_2 \left( \frac{Y_2}{\bar{Y}_2} + \frac{F_2^2}{2} \right) \quad (3-6-12)$$

When the flow is critical at section 2,  $F_2 = 1$ , then

$$Y_1 (2 + F_1^2) = \bar{Y}_2 \left( 2 \frac{Y_2}{\bar{Y}_2} + 1 \right) \quad (3-6-13)$$

or 
$$\frac{\bar{Y}_2}{Y_1} \frac{\left( 2 \frac{Y_2}{\bar{Y}_2} + 1 \right)}{(2 + F_1^2)} = 1 \quad (3-6-14)$$

The equation of continuity

$$(V_1 Y_1 B_1)^2 = (V_2 \bar{Y}_2 W)^2 \quad (3-6-15)$$

may be written

$$F_1^2 B^2 Y_1^3 = F_2^2 \bar{Y}_2^3 W^2 \quad (3-6-16)$$

which for  $F_2 = 1$  becomes

$$\left( \frac{\bar{Y}_2}{Y_1} \right)^3 = \left( \frac{B}{W} \right)^2 F_1^2 \quad (3-6-17)$$

Introducing this result into the specific energy equation (3-6-14) it follows that

$$F_1^2 \frac{B^2}{b^2} \frac{b^2}{W^2} \frac{\left( 2 \frac{Y_2}{\bar{Y}_2} + 1 \right)^3}{(2 + F_1^2)^3} = 1 \quad (3-6-18)$$

or 
$$\left( \frac{b}{B} \right)^2 = M^2 = F_1^2 \frac{b^2}{W^2} \left\{ \frac{2 \frac{Y_2/b}{\bar{Y}_2/b} + 1}{2 + F_1^2} \right\}^3 \quad (3-6-19)$$





As the value of the critical depth is a function of the critical flow factor

$$\frac{Y_c}{b} = f\left(\frac{Z}{b^{5/2}}\right) \quad (3-6-20)$$

and as the values of the free surface width  $W$ , and of the hydraulic depth  $\bar{Y}$  depend on  $Y_c$ , they are implicit functions of  $Z/b^{5/2}$ . Equation (3-6-20) may be then represented in a functional form as  $M = \left(\frac{b}{B}\right) = f\left(F_1, \frac{Z}{b^{5/2}}\right)$  for a given value of  $d/b$ .

This relationship is presented in Fig. 3-10 several values of  $d/b$  ranging from 0 to 4. The values of  $\frac{W}{b}$ ,  $\frac{Y}{b}$ ,  $\frac{\bar{Y}}{b}$  necessary for the preparation of these curves were obtained from Fig. 3-9 for values of  $Z/b^{5/2}$  of 0.1; 0.2; 0.3; 0.4; and 0.5. and introduced in formula (3-6-19) for  $M^2$  for several values of  $F_1$ .

For a given discharge  $Q$ , and a trial opening ratio  $b/B$  one may calculate the dimensionless section factor for critical flow

$$\frac{Z}{b^{5/2}} = \frac{Q^2}{\sqrt{g} b^{5/2}}$$

This value of this parameter defines a curve in Fig. 3-10. For points located above the curve, the flow is subcritical in the constriction. Points located on the curve correspond to flow going through critical in the constriction. The limiting backwater may be obtained by reading the value of  $F_1$  on Fig. 3-10 corresponding to given values of  $Z/b^{5/2}$ ,  $b/B$  and  $d/B$ , then  $Y_1$  is calculated from

$$Y_1^3 = Y_n^3 \left(\frac{F_1}{F_n}\right)^2 \quad (3-6-21)$$

For large discharge, the constrictions partially dam the flow, until it becomes an orifice flow.



### III-7 Discharge Equations

#### a) The Equation of Discharge for Free Surface Flow

With reference to Fig. 3-1 and neglecting the velocity of approach, the discharge is found to be  $Q = \int_0^{Y_1} V dA = \int_0^{Y_1} C \sqrt{2g(Y_1 - h)} \times 2\sqrt{r^2 - h^2} dh$  (3-7-1)

An approximate value of the above integral may be obtained by expanding the integrand into a series, and integrating term by term. Making use of the fact that  $2r = b$

$$Q = C_d \sqrt{2g} \cdot \frac{17}{24} Y_1^{3/2} b \left\{ \left(1 - 0.1294 \left(\frac{Y_1}{r}\right)^2 - 0.0177 \left(\frac{Y_1}{r}\right)^4 \dots \right\} \quad (3-7-2)$$

This may be written as

$$Q = C_1 Y_1^{3/2} b T_1 \quad (3-7-3)$$

where

$$C_1 = C_d \frac{17}{24} \sqrt{2g} \quad (3-7-4)$$

and

$$T_1 = 1 - 0.1294 \left(\frac{Y_1}{r}\right)^2 - 0.0177 \left(\frac{Y_1}{r}\right)^4 \quad (3-7-5)$$

The above equation is valid as long as the constriction is unsubmerged and  $Y_1 > r$ .

The evaluation of the equation of discharge in the integral form (equation 3-7-1) can be accomplished in two ways. One by expanding into a series and integrating term by term or by evaluating the integral in terms of complete and incomplete elliptical integrals of the first and second kind. The approximate solution was given above and the exact solution follows.

The theoretical discharge may be obtained from equation 3-7-1 by making the coefficient of discharge  $C_d$  equal to unity:

$$Q_t = 2\sqrt{2g} \int_0^{Y_1} \sqrt{(Y_1 - h)(r^2 - h^2)} dh \quad (3-7-6)$$

Let  $K^2 = \frac{Y_1 + r}{2r}$  or  $Y_1 = 2r(k^2 - 1)$ ,  $k < 1$ ,  $Y_1 < r$  (3-7-7)





and 
$$\operatorname{sn}^2 u = \frac{h+r}{Y_1+r} \quad (3-7-8)$$

Since 
$$\operatorname{sn}^2 u + \operatorname{cn}^2 u = 1$$

then 
$$h = Y_1 \operatorname{sn}^2 u - r \operatorname{cn}^2 u = 2rk^2 \operatorname{sn}^2 u - r \quad (3-7-9)$$

and 
$$\frac{dh}{du} = 4 \cdot rk^2 \operatorname{sn} u \frac{d}{du} \operatorname{sn} u = 4rk^2 \operatorname{sn} u \operatorname{cn} u \operatorname{dn} u \quad (3-7-10)$$

since 
$$\frac{d}{du} (\operatorname{sn} u) = \operatorname{cn} u \operatorname{dn} u$$

From (3-7-8) and making use of (3-7-7)

$$\begin{aligned} Y_1 - h &= Y_1 (1 - \operatorname{sn}^2 u) + r \operatorname{cn}^2 u \\ &= Y_1 \operatorname{cn}^2 u + r^2 \operatorname{cn}^2 u \\ &= 2rk^2 \operatorname{cn}^2 u \end{aligned} \quad (3-7-11)$$

Also from 3-7-8

$$\begin{aligned} r^2 - h^2 &= 4r^2 k^2 \operatorname{sn}^2 u (1 - k^2 \operatorname{sn}^2 u) \\ &= 4r^2 k^2 \operatorname{sn}^2 u \operatorname{dn}^2 u \end{aligned} \quad (3-7-12)$$

since 
$$\operatorname{dn}^2 u + k^2 \operatorname{sn}^2 u = 1$$

Substituting (3-7-10), (3-7-11) and (3-7-12) into (3-7-6) the expression for the theoretical discharge becomes

$$\begin{aligned} Q_t &= 2\sqrt{2g} \int_{u_1}^{u_2} \left[ 2rk^2 \operatorname{cn}^2 u \cdot 4r^2 k^2 \operatorname{sn}^2 u \operatorname{dn}^2 u \right]^{\frac{1}{2}} 4rk^2 \operatorname{sn} u \operatorname{dn} u \operatorname{cn} u \operatorname{du} = \\ &= 32\sqrt{g} r^{5/2} k^4 \int_{u_1}^{u_2} \operatorname{cn}^2 u \operatorname{sn}^2 u \operatorname{dn}^2 u \operatorname{du} \end{aligned} \quad (3-7-13)$$

The lower limit  $u_1$  is obtained from (3-7-8) as follows:

$$\operatorname{sn}^2 u_1 = \frac{0+r}{Y_1+r}$$



or 
$$\operatorname{sn} u_1 = \sin \phi = \sqrt{\frac{r}{Y_1 + r}}$$

where 
$$\phi = \operatorname{am} u_1$$

and finally 
$$u_1 = F(\phi, k) = \int_0^\phi \frac{d\phi}{\sqrt{1 - k^2 \sin^2 \phi}}, \quad k < 1 \quad (3-7-14)$$

$F(\phi, k)$  is the incomplete elliptic integral of the first kind.

the upper limit  $u_2$ , is obtained from (3-7-8) as follows:

$$\operatorname{sn}^2 u_2 = \frac{Y_1 + r}{Y_1 + r} = 1$$

or 
$$\operatorname{sn} u_2 = 1$$

and 
$$u_2 = K = \int_0^{\pi/2} \frac{d\phi}{\sqrt{1 - k^2 \sin^2 \phi}} \quad (3-7-15)$$

where  $K$  is the complete elliptic integral of the first kind

The expression for the theoretical discharge (3-4-13) becomes

$$Q_t = 32 \sqrt{g} \, r^{5/2} k^4 \int_{F(\phi, k)}^K \operatorname{cn}^2 u \operatorname{dn}^2 u \operatorname{sn}^2 u \, du \quad (3-7-16)$$

Upon performing the integration, and introducing the diameter  $b = 2r$

$$Q_t = \frac{4}{15} \sqrt{2g} \, b^{5/2} \left\{ 2(1 - k^2 + k^4) [E - E(\phi, k)] - (1 - k^2)(2 - k^2) [K - F(\phi, k)] - k^2 \sin \phi \cos \phi \Delta \phi (3k^2 \sin^2 \phi - 1 - k^2) \right\} \quad (3-7-17)$$

where 
$$E = \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2 \phi} \, d\phi \quad (3-7-18)$$

which is the complete elliptic integral of the second kind, and

$$E(\phi, k) = \int_0^\phi \sqrt{1 - k^2 \sin^2 \phi} \, d\phi \quad (3-7-19)$$



which is the incomplete elliptic integral of the second kind, and

$$\phi = \sin^{-1} \sqrt{\frac{r}{y_1 + r}} \quad (3-7-20)$$

and

$$A \phi = \sqrt{1 - k^2 \sin^2 \phi} = \sqrt{0.5} \quad (3-7-21)$$

and finally

$$k = \sqrt{\frac{y_1 + r}{b}} \quad (3-7-22)$$

Equation (3-7-17) yields the theoretical discharge for the flow through a semicircular constriction of diameter  $b = 2r$  and where the maximum depth upstream of the constriction is  $y_1$ . The quantities  $K$ ,  $E$ ,  $F(\phi, k)$ ,  $E(\phi, k)$  may be obtained from tables.

Equation (3-7-17) is somewhat similar to that for the flow through circular weirs obtained by J. C. Stevens<sup>7</sup> which is

$$Q_t = \frac{4}{15} \sqrt{2g} D^{5/2} \{ 2(1 - k^2 + k^4) E - (2 - k^2)(1 - k^2) K \} \quad (3-7-23)$$

where  $k^2 = H/D$ ,  $H$  being the head over the invert, and  $D$  is the diameter of the circular weir. Stevens also gives an infinite series approximation to equation (3-7-23) which is similar to equation (3-7-2):

$$Q_t = 2 \sqrt{2g} D^{5/2} \left( \frac{1}{8} z^2 - \frac{1}{32} z^3 - \frac{5}{1024} z^4 \dots \right) \quad (3-7-24)$$

where  $z = H/D$ .

#### b) The Equation of Discharge for Orifice Flow

With reference to Fig. 3-11 and neglecting the velocity of approach, the discharge is found to be:

$$Q = \int V dA = 2 Cd \sqrt{2g} \int_0^r (y_1 - h)^{\frac{1}{2}} (r^2 - h^2)^{\frac{1}{2}} dh \quad (3-7-25)$$

An approximate solution to the above integral is found by expanding each term of the integrand into a binomial series, multiplying the two series and integrating term by term. The result, using the 5 leading terms is





$$Q = 0.4019 C_d \sqrt{2g} Y_1^{\frac{1}{2}} b^2 \left[ 1 - 0.2136 \left( \frac{r}{Y_1} \right) - 0.03216 \left( \frac{r}{Y_1} \right)^2 - 0.0112 \left( \frac{r}{Y_1} \right)^3 - 0.005344 \left( \frac{r}{Y_1} \right)^4 \dots \right] \quad (3-7-26)$$

or 
$$Q = C_1 Y_1^{\frac{1}{2}} b^2 T \quad (3-7-27)$$

where 
$$C_1 = 0.4019 \sqrt{2g} \quad C_d = 3.22 C_d \quad (3-7-28)$$

and 
$$T = 1 - 0.2136 \left( \frac{r}{Y_1} \right) - 0.03216 \left( \frac{r}{Y_1} \right)^2 - 0.0112 \left( \frac{r}{Y_1} \right)^3 - 0.005344 \left( \frac{r}{Y_1} \right)^4 \quad (3-7-29)$$

The above equation is valid as long as the constriction is submerged, which means for  $Y_1 > r$ .

A simpler form of the orifice discharge equation when the approach velocity is very low relative to the velocity in the discharge jet, and when the orifice is considered as a whole is:

$$Q = C_d^{\frac{1}{2}} \frac{\pi d^2}{4} \sqrt{2g Y_1} \quad (3-7-30)$$

where  $Q$  = discharge through the opening

$d$  = diameter of the opening

and  $Y_1$  = the depth of the backwater

$C_d$  = coefficient of discharge for type of inlet

Now rearranging equation (3-7-30):

$$\frac{Q^2}{g d^4} = \frac{C_d^2 \pi^2}{32} Y_1 \quad (3-7-31)$$

By dividing by  $d^4$ , and taking the square root of both sides of (3-7-31), the following dimensionless equation is obtained



$$\frac{Q}{g^{\frac{1}{2}} d^{5/2}} = \frac{C_d \pi}{\sqrt{32}} \left( \frac{Y_1}{d} \right)^{\frac{1}{2}} \quad (3-7-32)$$

where  $\frac{C_d \pi}{\sqrt{32}}$  is a constant.

The previous equation may be written in the general form

$$\frac{Q}{g^{\frac{1}{2}} d^{5/2}} = f \left( \frac{Y_1}{d} \right) \quad (3-7-33)$$

which is used in plotting experimental results.

$$\frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} = \frac{1}{2}$$

$$\frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} = \frac{1}{2}$$

The product of two numbers is 1/2.

$$\frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}} = \frac{1}{2}$$

The product of two numbers is 1/2.



### III-8 Energy Loss in the Constriction

It has been shown that a complete theoretical analysis is not possible. However, some important conclusions regarding the classification of flow types and limiting cases have been obtained from momentum and energy considerations. The applicability of the momentum and energy equations is limited principally by the difficulty of formulating the drag force and the head losses. Izzard<sup>8</sup> and Bradley<sup>9</sup> have proposed an empirical relation for the head loss in a constriction. The head loss due to the contraction and expansion of the flow may be expressed as

$$h = K \frac{V_{2n}^2}{2g} \quad (3-8-1)$$

where  $V_{2n}$  is a reference velocity, which is given by

$$V_{2n} = \frac{Q}{A_{2n}} \quad (3-8-2)$$

where  $A_{2n}$  is the area of section 2 corresponding to the normal depth in the uncontracted flow.

The energy equation, written between sections 1 and 4 is:

$$Y_1 + \alpha_1 \frac{V_1^2}{2g} + S_o L_{1-4} = Y_4 + \alpha_4 \frac{V_4^2}{2g} + E_{1-4} \quad (3-8-3)$$

where  $E_{1-4}$  is the total energy loss between sections 1 and 4. This energy loss is made of two parts: the normal boundary resistance plus the additional loss due to the contraction and expansion of the flow:

$$E_{1-4} = S_o L_{1-4} + K \frac{V_{2n}^2}{2g} \quad (3-8-4)$$

Replacing in the energy equation

$$Y_1 - Y_4 = K \frac{V_{2n}^2}{2g} + \alpha_4 \frac{V_4^2}{2g} - \alpha_1 \frac{V_1^2}{2g} \quad (3-8-5)$$



Since at section 4 the normal depth has been regained  $Y_4 = Y_n$ , and making use of the continuity equation

$$V_1 A_1 = V_4 A_4 = V_{n2} A_{n2} \quad (3-8-6)$$

$$Y_1 - Y_n = h_1^* = K \frac{V_{n2}^2}{2g} \left[ \alpha_4 \left( \frac{A_{n2}}{A_4} \right)^2 - \alpha_1 \left( \frac{A_{n2}}{A_1} \right)^2 \right] \frac{V_{n2}^2}{2g} \quad (3-8-7)$$

from which 
$$K = \frac{h_1^*}{V_{n2}^2/2g} \left[ \alpha_4 \left( \frac{A_{n2}}{A_4} \right)^2 - \alpha_1 \left( \frac{A_{n2}}{A_1} \right)^2 \right] \quad (3-8-8)$$

or approximately 
$$K = h_1^*/(Y_{n2}^2/2g) \quad (3-8-9)$$

The same results are valid for submerged constriction, when the total cross sectional area of the constriction  $A_0$  is taken as reference area instead of  $A_{n2}$ . Then the head loss due to the contraction and expansion of the flow is written as

$$h_f = K \frac{V_o^2}{2g} \quad (3-8-10)$$

where 
$$V_o = \frac{Q}{A_o} \quad (3-8-11)$$

and as before 
$$h_1^* = K \frac{V_o^2}{2g} \left[ \alpha_4 \left( \frac{V_4}{V_o} \right)^2 \frac{V_o^2}{2g} - \alpha_1 \left( \frac{V_1}{V_o} \right)^2 \frac{V_o^2}{2g} \right] \quad (3-8-12)$$

and 
$$K = \frac{h_1^*}{V_o^2/2g} \left[ \alpha_4 \left( \frac{A_o}{A_4} \right)^2 - \alpha_1 \left( \frac{A_o}{A_1} \right)^2 \right] \quad (3-8-13)$$

In formulas 7-8-7, 7-8-8 and 7-8-12, 7-8-13, a simplification may be obtained by assuming  $\alpha_1 = \alpha_4 = \alpha$ .

An alternate simplified expression for the head loss in the contracting flow may be obtained by considering the contraction as an orifice, and by assuming that the depth at the orifice is the normal depth. With these assumptions, and neglecting the velocity head of approach  $V_{n1}^2/2g$ , the energy equation yields



$$\frac{V_{n2}^2}{2g} = Y_1 - Y_n \quad (3-8-14)$$

Introducing a coefficient of velocity

$$C_v = C_v (M^2, F) \quad (3-8-15)$$

where  $M^2$  is the channel opening ratio, then

$$V_{n2}^2 = C_v^2 2g (Y_1 - Y_n) \quad (3-8-16)$$

Introducing an orifice Froude number defined by

$$F_o^2 = \frac{V_{n2}^2}{g Y_n} = 2C_v^2 \left( \frac{Y_1}{Y_n} - 1 \right) \quad (3-8-17)$$

then

$$\frac{Y_1}{Y_n} - 1 = \frac{1}{2} \left( \frac{F_o}{C_v} \right)^2 \quad (3-8-18)$$

But as

$$\left( \frac{F_o}{F_n} \right)^2 = \left( \frac{V_{n2}}{V_{n1}} \right)^2 = \left( \frac{A_{n2}}{A_{n1}} \right)^2 = \left( \frac{1}{M^2} \right)^2 \quad (3-8-19)$$

then

$$\frac{Y_1}{Y_n} - 1 = \frac{1}{2C_v^2} \left( \frac{F_n}{M^2} \right)^2 \quad (3-8-20)$$

The head loss through an orifice is given by

$$h_f = \left( \frac{1}{C_v^2} - 1 \right) \frac{V^2}{2g} \quad (3-8-21)$$

so that the head loss in the contracting flow is, in dimensionless form,

$$\frac{h_f}{Y_n} = \left( \frac{1}{C_v^2} - 1 \right) \frac{V_{n2}^2}{2g Y_n} = \frac{1}{2} \left( \frac{1}{C_v^2} - 1 \right) \left( \frac{F_n}{M^2} \right)^2 \quad (3-8-22)$$

But, by means of (3-8-20)





$$\frac{1}{C_v^2} - 1 = \frac{2 \left( \frac{Y_1}{Y_n} - 1 \right)}{\left( \frac{F_n}{M_1} \right)^2} - 1 \quad (3-8-23)$$

and (7-8-22) becomes:

$$\frac{h_f}{Y_n} = \left( \frac{Y_1}{Y_n} - 1 \right) + \frac{1}{2} \left( \frac{F_n}{M_1} \right)^2 \quad (3-8-24)$$

As experiments have shown that in general

$$\frac{Y_1}{Y_n} = f \left( \frac{F_n}{M_1} \right)^2$$

then, in general

$$\frac{h_f}{Y_n} = f \left( \frac{F_n}{M_1} \right)^2 \quad (3-8-25)$$



### III-9 Backwater Ratio Equations

The backwater ratio is defined as the ratio of the maximum centerline water depth to the normal depth of flow.

Expressions for the backwater ratio may be obtained from the energy equation or from the discharge equation. The use of the energy equation will be considered first.

The energy equation is written in dimensionless form by dividing both sides by  $Y_n$ :

$$\frac{h_1^*}{Y_n} = \frac{1}{2} \left( \frac{F_n}{M^0} \right)^2 \left[ \alpha_4 M^0{}^2 - \alpha_1 M^0{}^2 \left( 1 - 2 \frac{h_1^*}{Y_n} \right) + K \right] \quad (3-9-6)$$

Assuming  $\alpha_1 = \alpha_4 = \alpha$  it follows that

$$\frac{h_1^*}{Y_n} = \frac{1}{2} \left( \frac{F_n}{M^0} \right)^2 \left[ 2 M^0 \frac{h_1^*}{Y_n} + K \right] \quad (3-9-7)$$

or

$$\frac{h_1^*}{Y_n} \left[ 1 - \alpha F_n^2 \right] = \frac{1}{2} \left( \frac{F_n}{M^0} \right)^2 K \quad (3-9-8)$$

whence

$$\frac{h_1^*}{Y_n} = \left( \frac{F_n}{M^0} \right)^2 \frac{\frac{1}{2} K}{1 - (F_n)^2 \alpha} \quad (3-9-9)$$

In general, the expression for the backwater ratio for free surface flow is:

$$\frac{h_1^*}{Y_1} = D \left( \frac{F_n}{M^0} \right)^2 \quad (3-9-10)$$

where

$$D = \frac{1/2 K}{1 - (F_n)^2 \alpha} \quad (3-9-11)$$

is a factor related to the head loss in the constriction.

This result is valid only when the flow is subcritical through the constriction and when  $h_1^*/Y_n < 1$ .





Experimental results have yielded the empirical relation (for single span semi-circular arches, see Chapter V),

$$\frac{h_1^*}{Y_n} = 0.45 \left( \frac{F_n}{M^2} \right)^2 \quad (3-9-12)$$

with this result

$$D = \frac{1/2 K}{1 - F_n^2 \alpha} = 0.45 \quad (3-9-13)$$

$$\text{or} \quad K = 0.90 (1 - \alpha F_n^2) \quad (3-9-14)$$

$$\text{or with } \alpha = 1 \quad K = 0.90 (1 - F_n^2) \quad (3-9-15)$$

The test results are presented in the form of plots of  $\frac{h_1^*}{Y_1}$  vs  $\left( \frac{F_n}{M^2} \right)^2$  and least square curves of the form

$$\frac{h_1^*}{Y_n} = C \left( \frac{F_n^2}{M^2} \right)^n \quad (3-9-16)$$

are obtained. As from equation (3-9-10), D is the slope of the curve of  $h_1^*/Y_n$  vs  $(F_n/M^2)^2$ , it follows from equation (3-9-16) that

$$\frac{d\left(\frac{h_1^*}{Y_n}\right)}{d\left(\frac{F_n^2}{M^2}\right)} = nC \left( \frac{F_n^2}{M^2} \right)^{n-1} = D \quad (3-9-17)$$

Alternate expressions for the backwater ratio may be obtained from the discharge equation for free surface and for orifice flow separately.

Consider the free surface flow case first. The equation for the discharge through the constriction is (from equ. 3-7-3)

$$Q = C_1 Y_1^{3/2} b T_1 \quad (3-9-18)$$

$$\text{where} \quad C_1 = Cd \frac{17}{24} \sqrt{2g} \quad (3-9-19)$$

$$\text{and} \quad T_1 = 1 - 0.1294 \left( \frac{Y_1}{x} \right)^2 - 0.0177 \left( \frac{Y_1}{x} \right)^4 \quad (3-9-20)$$



The discharge in the approach channel is

$$Q = V_n A_n = F_n \sqrt{g} B Y_n^{3/2} \quad (3-9-21)$$

Equating the two expressions for the discharge one obtains

$$\frac{Y_1}{Y_n} = \left[ \frac{12 \sqrt{2} F_n}{17 C_d M T_1} \right]^{2/3} \quad (3-9-22)$$

or in general

$$\frac{Y_1}{Y_n} = C \left( \frac{F_n}{M^3} \right)^{2/3} \quad (3-9-23)$$

where

$$C = \frac{12 \sqrt{2} C_d}{17 C_d T} \quad (3-9-24)$$

Since  $M = M^3 / C_m$  (see equation 3-10-8)

Experimental results for free surface flow have yielded the following relation  
(see chapter VII)

$$\frac{Y_1}{Y_n} = 1 + 0.47 \left[ \left( \frac{F_n}{M^3} \right)^{2/3} \right]^{3.39} \quad (3-9-25)$$

It has been observed that the equations derived by several different investigators for the backwater ratio produced by various constriction geometries seem to have a basic similarity. As an example, equation (23) in the present text for  $y_1/y_n$  appears to be a function of  $(F/M^3)^{2/3}$ .

$$y_1/y_n = g_1 (F_n/M^3)^{2/3} \quad (3-9-26)$$

An equation for the backwater ratio given by Valentine<sup>8</sup> for lateral constriction in plates is

$$y_1/y_n = (g F_n / C M)^{2/3} = g_2 (F_n/M^3)^{2/3} \quad (3-9-27)$$

where  $C$  = a discharge coefficient

and  $M = b/B = M^3$  since  $C_M = 1$

Also Liu et al<sup>11</sup> present an empirical formula for a two dimensional vertical board model



$$(h_1^*/h_n)^3 = 4.483 F_n^2 \left( \frac{1}{M^2} - \frac{2}{3} (2.5 - M) \right) - 1 \quad (3-9-28)$$

where  $M = b/B = M^0$  since  $C_M = 1$

Considering only the leading term  $1/M^2$  of the quantity in brackets, equation (3-9-28) becomes

$$h_1^*/y_n = g_3 (F_n/M^0)^{2/3} \quad (3-9-29)$$

It appears that with the proper interpretation of the variables, namely  $M^0$  and  $F_n$ , the results of tests performed on different geometric shapes of bridge openings should produce the same results. For instance, a vertical abutment deck type bridge may physically appear completely different than a semicircular arch bridge. However, hydraulically speaking if they have the same opening ratio  $M^0$ , they should produce the same backwater ratio. The limitations of the assumption must necessarily lie in the fact that both bridges must have the same eccentricity, skewness and entrance rounding conditions. It is believed that this concept applies equally as well to multiple span bridges. An attempt has been made to compare the two dimensional semicircular test results of the author, the segment data obtained by A. A. Socky, and the Vertical Board (VB) data as given by Liu<sup>11</sup>. The results of this comparison will be shown and discussed in a later section.

A similar expression for the backwater ratio may be obtained from the theoretical discharge equation for orifice flow. The equation for the discharge through the constriction was found to be: (see equ. 3-7-27)

$$Q = C_1 Y_1^{1/2} b^2 T \quad (3-9-30)$$

The discharge in the approach channel is:

$$Q = V_n A_n = F_n \sqrt{g} B Y_n^{3/2} \quad (3-9-31)$$

Equating the two discharge equations (3-9-30 and 3-9-31):

$$C_1 Y_1^{1/2} b^2 T = F_n \sqrt{g} Y_n^{3/2} B \quad (3-9-32)$$



$$(h_1^2/h_2^2) = 2.5 \times 10^{-6} \left( \frac{2}{1.5} \right) = 3.3 \times 10^{-6}$$

$$h_1 = h_2 = 0.1 \text{ cm}$$

Considering only the leading term in  $S$  of the expansion of  $S$  in powers of  $h_1$  and  $h_2$

$$S \approx \frac{1}{2} \pi h_1^2 + \frac{1}{2} \pi h_2^2$$

It appears that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

$$Q = 2.1 \times 10^{-6} \text{ r}$$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

the results of the calculation of the term  $\frac{1}{2} \pi h_1^2$  are shown in Table I

It is seen from Table I that the term  $\frac{1}{2} \pi h_1^2$  is the dominant term in the expansion of  $S$  in powers of  $h_1$  and  $h_2$

and

$$C_1 = \left( \frac{Y_1}{Y_n} \right)^3 \frac{F_n B Y_n}{b^2 T} = \left( \frac{Y_n}{Y_1} \right)^3 \left( \frac{B}{b} \cdot \frac{Y_n}{b} \right) F_n \frac{1}{T} \quad (3-9-33)$$

but

$$\frac{B}{b} \cdot \frac{Y_n}{b} = \frac{A_n}{k A_0} = \frac{1}{k M^2}$$

where

$$k = \frac{8}{\pi}$$

Now rearranging the equation (3-9-33):

$$\frac{Y_1}{Y_n} = \left( \frac{1}{k M^2} F_n \cdot \frac{1}{C_1} \cdot \frac{1}{T} \right)^2 \quad (3-9-34)$$

or in general a relation of the following form would be expected

$$\frac{Y_1}{Y_n} = C \left( \frac{F_n}{M^2} \right)^2 \quad (3-9-35)$$

It has been found empirically that, instead of equation (3-9-35), the experimental results can conveniently be represented by a function of the form:

$$\frac{h_1^*}{Y_n} = \frac{Y_1}{Y_n} - 1 = f \left( \frac{F_n}{M^2} \right)^2 \quad (3-9-36)$$

where  $h_1^*$  is the backwater superelevation.

Experimental results for the orifice flow have yielded the following relation (see Chapter VII)

$$\frac{Y_1}{Y_n} = 1 + 1.18 \left[ \left( \frac{F_n}{M^2} \right)^2 \right]^{0.90} \quad (3-9-37)$$

or

$$\frac{Y_1}{Y_n} = 1 + 1.18 \left( \frac{F_n}{M^2} \right)^{1.80} \quad (3-9-38)$$

The experimental result for the backwater ratio equation for free surface was developed by P. F. Biery and found to yield the relation (see chapter V)



$$\frac{Y_1}{Y_n} = 1 + 0.47 \left[ \left( \frac{F_n}{M^0} \right)^{2/3} \right] \quad 3.39 \quad (3-9-39)$$

or

$$\frac{Y_1}{Y_n} = 1 + 0.47 \left( \frac{F_n}{M^0} \right)^{2.26} \quad (3-9-40)$$





### III-10 Dimensional Consideration

#### a) Dimensional Analysis

Figure 3-1 shows a definition sketch of the effects of a channel constriction on the water surface profile. Section view B illustrates the type of centerline profile obtained with a Class I flow. This is the most generally occurring situation that appears in actual practice. In the figure  $Y_0$  or  $Y_n$  is the normal depth of the unobstructed channel.  $Y_1$  is the depth at the point of maximum backwater elevation.  $Y_2$  is the depth at the section of minimum jet area or the vena contracta.  $Y_3$  is the minimum water depth of the regain curve, and  $Y_4$  is at a point sufficiently downstream from the contraction where the flow returns to the normal depth.

For any physical problem such as this, a dimensional analysis is convenient for the purpose of guidance and interpretation of a testing program. In this manner, the basic variables can be grouped into dimensionless quantities and their relationships investigated. In the problem at hand, it is desired to determine the maximum water depth upstream of the constriction. It is assumed that the variables which govern the backwater superelevation may be grouped into three categories as follows: the fluid properties, the kinematic and dynamic variables, and the dimensions defining the boundary geometry. Due to the two dimensional character of the constriction, the latter is expressed in terms of flow areas rather than the usual linear dimensions. (See figure 3-1 for an illustration of the terminology.)

The variables are:

#### a) Fluid Properties

- 1)  $\nu$ , the kinematic viscosity of the fluid
- 2)  $\rho$ , density of the fluid

#### b) Kinematic and Dynamic Flow Variables

- 1)  $g$ , acceleration of gravity
- 2)  $Y_1$ , maximum water depth upstream of the constriction

a) Physical Properties

Figure 1-1 shows the physical properties of the material.

on the water surface. The material is a solid, and the profile obtained is a solid line.

that appears in the water surface. The material is a solid, and the profile obtained is a solid line.

undisturbed. The material is a solid, and the profile obtained is a solid line.

is a solid line. The material is a solid, and the profile obtained is a solid line.

minimum. The material is a solid, and the profile obtained is a solid line.

from the water surface. The material is a solid, and the profile obtained is a solid line.

is a solid line. The material is a solid, and the profile obtained is a solid line.

For the purpose of the study, the material is a solid, and the profile obtained is a solid line.

the water surface. The material is a solid, and the profile obtained is a solid line.

shape. The material is a solid, and the profile obtained is a solid line.

water surface. The material is a solid, and the profile obtained is a solid line.

govern the water surface. The material is a solid, and the profile obtained is a solid line.

the water surface. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

definite. The material is a solid, and the profile obtained is a solid line.

- 3)  $Y_n$ , the normal depth of flow in the approach channel.
  - 4)  $V_n$ , the velocity of flow at normal depth
  - 5)  $n$ , Manning's roughness coefficient of the approach channel.
- c) Properties of the Constriction Geometry (see figures 2, 4, and 24 for definition of symbols).
- 1)  $A_{n1}$ , the total normal depth flow area at section 1.
  - 2)  $A_{n2}$ , the normal depth flow area in the opening of the constriction (see Fig. 4).  $A_{n2} = A_0$  for submerged bridges.
  - 3)  $L/b$ , thickness factor, where  $L$  is the length of bridge in direction of flow,  $b$  is the width of opening at the bottom.
  - 4)  $bL_d/A_{n2}$ , distance factor where  $L_d$  is the distance between two parallel identical bridges.
  - 5)  $\phi_1$ , wing wall angles
  - 6)  $\phi_2$ , skew angle
  - 7)  $\beta$ , segment factor defined by  $\beta = d/r$  where  $d$  is the distance between the channel bottom and the center of the circular segment.
  - 8)  $N$ , number of spans
  - 9)  $e$ , eccentricity defined by  $e = 1 - c/a$ , where  $c$  and  $a$  are the width on either sides of the bridge openings.

From the above list of variables,

$$Y_1 = f_1 (Y_n, V_n, n, \nu, h, V, \beta, \xi, A_{n1}, A_{n2}, L/b, \frac{bL_d}{A_{n2}}, \phi_1, \phi_2, e, \beta, N)$$

Buckingham's theorem states that in a physical problem including  $n$  quantities in which there are  $m$  dimensions, the quantities may be arranged into  $(n-m)$  dimensionless parameters. With the mass, length and time system of units, the  $n-m$  or 14 dimensionless parameters are as follows:

$$\frac{Y_1}{Y_n} = f_2 \left( \frac{V_n^2}{Y_n g}, \frac{V_n Y_n}{\nu}, \frac{n}{Y_n^{1/6}}, \frac{A_{n1}}{Y_n^2}, \frac{A_{n2}}{Y_n^2}, \frac{h}{Y_n}, \frac{L}{b}, \frac{bL_d}{A_{n2}}, \phi_1, \phi_2, e, \beta, N \right)$$





where  $\frac{V_n^2}{Y_n g}$  is the square of the Froude number  $F_n$  and  $\frac{V_n Y_n}{\nu}$  is the Reynolds number  $R$ . It is known that:

- 1) Viscous forces play a negligible role in open channel flow. So the term  $R$  can be neglected. Furthermore, by combining the ratio  $A_{n2}/Y_{n2}$  and  $A_{n1}/Y_n^2$  into  $A_{n2}/A_{n1} = M^0$ , and letting  $n$  be constant, which means that the boundary roughness in the flume is kept the same, then the above equation simplifies to:

$$\frac{Y_1}{Y_n} = f(F_n, M^0, \frac{L}{b}, \frac{bLd}{A_{n2}}, \phi_1, \phi_2, e, \beta, N) \quad (3-10-1)$$

Of the nine variables only two, the Froude number and the contraction ratio describe the flow field. The other seven variables in the dimensionless analysis describe the different model geometries that could be tested separately. For a definition of the separate geometries see section on Definition of Test Geometries.

#### b) Definition of Channel Opening Ratio and Channel Width Ratio

The channel opening ratio ( $M^0$ ) is defined as that portion of the total normal depth flow that can pass through the bridge waterway without contraction. By definition it is equivalent to the ratio  $A_{n2}/A_{n1}$  obtained from the dimensional analysis. Along with the normal depth Froude number, the opening ratio is perhaps the most critical variable in the problem.

Referring to figure 3-12-a for the rectangular case, the total flow is that flow in area ADEH, and the flow that passes through the bridge opening without contraction is that represented by the area BCFG. Therefore the opening ratio  $M^0$  is

$$M^0 = q/Q \quad (3-10-2)$$

If we assume that there is a constant uniform velocity  $V_n$  across the entire normal depth section, equation ( 3-10-2 ) becomes

$$M^0 = q/Q = A_{n2}V_n/A_{n1}V_n = A_{n2}/A_{n1} = b_{Yn}/B_{Yn} = b/B \quad (3-10-3)$$





However, for an arch bridge, as shown also in figure (3-12-b), the surface width will be different for each and every normal depth  $y_n$ . Therefore in the same manner:

$$M^i = q/Q = A_{n2}V_n/A_{n1}V_n = A_{n2}/A_{n1} \quad (3-10-4)$$

The ratio of the two areas is clearly not equivalent to  $b/B$ . (for simplicity,  $b/B$  is hereafter defined by the symbol  $M$ )

For the portion GIKF of a semicircular arch with radius  $r$  and depth  $y_n$  the area becomes

$$A_{n2} = \int_0^{y_n} 2\sqrt{r^2 - y^2} dy = 2 \left[ \frac{1}{2} \{ y_n \sqrt{r^2 - y_n^2} + r^2 \sin^{-1} y_n/r \} \right] \quad (3-10-5)$$

The segment of arch GECF shown in figure 3-12-b has a radius  $r$  and springline width  $b$ . The arch has been superimposed upon the flow area of depth  $y_n$ . The center of curvature is at a distance  $d$  below the springline of the arch. The flow area ( $A_{n1}$ ) of the rectangular channel is  $B y_n$ , while the area GECF is given by

$$A_{n2} = \int_0^D 2\sqrt{r^2 - y^2} dy - \int_0^d 2\sqrt{r^2 - y^2} dy \quad (3-10-6)$$

and the corresponding channel opening ratio is

$$M^i = A_{n2}/A_{n1} = \frac{D\sqrt{r^2 - D^2} + r^2 \sin^{-1} D/r}{B y_n} - \frac{d\sqrt{r^2 - d^2} + r^2 \sin^{-1} d/r}{B y_n} \quad (3-10-7)$$

The channel opening ratio  $M^i$  can be expressed in terms of three other dimensionless ratios: the ratio of span to channel width  $M = b/B$ , the ratio of depth of the arch center below the streambed to the arch radius  $\eta = d/r$  and the ratio of normal depth to arch radius  $\zeta = y_n/r$ . The channel opening ratio of equation (3-10-7) may thus be expressed as:

$$M^i = M C_M \quad (3-10-8)$$

in which

$$M = b/B$$

and the channel opening ratio coefficient is

$$C_M = \frac{1}{2} \left[ \left\{ \frac{\sqrt{1-(\eta\zeta)^2} + \frac{1}{(\eta\zeta)} \sin^{-1} (\eta\zeta)}{\frac{\zeta}{\eta+5} (1-\eta^2)^{1/2}} \right\} - \left\{ \frac{\sqrt{1-\eta^2} + \frac{1}{\eta} \sin^{-1} \eta}{\frac{\zeta}{\eta} (1-\eta^2)^{1/2}} \right\} \right] \quad (3-10-9)$$

the number of the

$$dH = \frac{1}{2} \left( \frac{d^2 H}{dt^2} \right) dt^2$$

is the number of the

with  $\eta = d/r$

and  $\zeta = y_n/r$

In the form of equation (3-10-8) the value of  $M = b/B$  is adjusted for the particular arch by an amount equivalent to  $C_M$  such that  $M^0$  is the same as the ratio of  $A_{n2}$  to  $A_{n1}$ . In the more general case, the values of  $\zeta$  and  $\eta$  can take on numbers within certain limits, before the normal depth will submerge the crown of the arch. The limits are as follows:

$$\text{For } \zeta = y_n/r \quad 0/r \leq y_n/r \leq (r-d)/r \quad (3-10-10)$$

or

$$0 < \zeta < (1 - \eta)$$

$$\text{For } \eta = d/r \quad 0 < \eta < 1 \quad (3-10-11)$$

When  $\eta = 0$ , the case of a semicircular arch with the center of curvature at the springline exists. When  $\eta = 1$ , the contraction reduces to two parallel abutments.

The values of  $C_M$  have been calculated for several values of  $\zeta$  and  $\eta$  and are summarized in the graph of figure 3-13. The submergence limit represents the upper limits of both  $\zeta$  and  $\eta$ . The segment arch which is a constant radius arch with its center of curvature below the springline of the arch (i.e.  $\eta > 0$ ) can be used as an arch in its own right or as an approximation to an elliptical or a multiple radius arch. The value of  $M^0$  for the elliptic and multiple radius arch could be determined directly from equation (3-10-4).





### III-11 Definition of Test Geometries - Selection of Tests

Nine independent variables were considered in the dimensional analysis to determine the dependent variable  $Y_1/Y_n$ . Of these nine variables, seven describe different types of constriction geometries, the other two, the Froude number and the contraction ratio describe the flow field and the amount of contraction. These seven geometric variables were used to define seven types of geometries that were tested separately. These types of geometries are defined below.

#### Geometry I-a

##### Two-Dimensional Semicircle Arch Bridge Constrictions:

(Figure 3-14) The characteristics of this type of geometry are the following:

- Since the model is two-dimensional,  $\frac{L}{b} = 0$
- Single bridge case,  $L_d = 0$  and  $\frac{bL_d}{An2} = 0$
- No wingwalls, according to definition of  $\phi_1$ ,  $\phi_1 = 90^\circ$
- None-skew case, according to definition of  $\phi_2$ ,  $\phi_2 = 0^\circ$
- Semicircular case,  $d = 0$  and  $\beta = \frac{d'}{r} = 0$
- One span case,  $N = 1$
- No eccentricity,  $e = 0$
- Froude number,  $F_n = \frac{V_n}{(gY_n)^{1/2}}$  designated as an independent variable.
- Constriction opening ratio  $M^0$ , designated as an independent channel opening ratio  $M^0$

Hence, seven independent descriptive variables,  $\frac{L}{b}$ ,  $\frac{bL_d}{An2}$ ,  $e$ ,  $\phi_1$ ,  $\phi_2$ ,  $\beta$  and  $N$  in the dimensionless equation: (3-10-1).  $\frac{Y_1}{Y_n} = f(F_n, M^0, \frac{L}{b}, \frac{bL_d}{An2}, \phi_1, \phi_2, e, \beta, N)$  are designated as constants and we get the relation:

$$\frac{Y_1}{Y_n} = f(F_n, M^0)$$



Geometry I-bThree-Dimensional Semicircular Arch Bridges:

This geometry differs from the previous one only in that  $L$  is varied, thus the parameter  $\frac{L}{b}$  describing the length of the model in the direction of the flow is a variable and the dimensionless equation (3-10-1) for this case becomes

$$\frac{Y_1}{Y_n} = f(F_n, M^0, \frac{L}{b})$$

Geometry IIDual Parallel Three-Dimensional Arch Bridge Constrictions:

This geometry consists of two identical bridges of geometry I-b, placed at distance  $L_d$  apart, measured center to center. One new variable,  $L_d$ , is introduced, which is characterized by the parameter  $\frac{BL_d}{A_{n2}}$  (Note: For submerged bridge constrictions,  $A_{n2} = A_0$ , see Chapter III). Equation (3-10-1) simplifies for this case to:

$$\frac{Y_1}{Y_n} = f(F_n, M^0, \frac{bL_d}{A_{n2}})$$

Geometry IIIThree-Dimensional Arch Bridge Constriction with Wingwalls:

The geometric characteristics were as follows:

a)  $\frac{L}{b} = 0.25$

e)  $\beta = 0$

b)  $\frac{bL_d}{A_{n2}} = 0$

f)  $N = 1$

c)  $\phi_1$  is a variable  $0_1 = 90^\circ, 60^\circ, 45^\circ, \text{ or } 30^\circ$

g)  $\alpha = 0$

d)  $\phi_2 = 0^\circ$

h)  $F_n$  is a variable

i)  $M^0$  is a variable

Hence, equation (3-10-1) can be simplified to:

# Section 1.1

## Three-dimensional Cartesian System

This geometry differs from the previous one in that it is a three-dimensional space. The axes are labeled  $x$ ,  $y$ , and  $z$ . The origin is labeled  $O$ . The distance from the origin to a point  $P$  is labeled  $\rho$ . The angle between the  $z$ -axis and the line segment  $OP$  is labeled  $\theta$ . The angle between the  $x$ -axis and the projection of  $OP$  on the  $xy$ -plane is labeled  $\phi$ .

$$\rho = \sqrt{x^2 + y^2 + z^2}$$

$$\theta = \arccos \frac{z}{\rho}$$

$$\phi = \arccos \frac{x}{\sqrt{x^2 + y^2}}$$

### Direction Cosines

#### Direction Cosines of a Vector

The direction cosines of a vector  $\mathbf{r}$  are the cosines of the angles between the vector and the positive  $x$ ,  $y$ , and  $z$  axes. They are denoted by  $\alpha$ ,  $\beta$ , and  $\gamma$  respectively. The direction cosines satisfy the identity  $\alpha^2 + \beta^2 + \gamma^2 = 1$ .

$$\alpha = \frac{x}{\rho}, \beta = \frac{y}{\rho}, \gamma = \frac{z}{\rho}$$

### Directional Derivatives

#### Directional Derivative of a Scalar Field

The directional derivative of a scalar field  $\phi$  in the direction of a unit vector  $\mathbf{u}$  is denoted by  $\frac{d\phi}{ds}$ .

$$\frac{d\phi}{ds} = \nabla \phi \cdot \mathbf{u}$$

$$\frac{d\phi}{ds} = \frac{\partial \phi}{\partial x} \alpha + \frac{\partial \phi}{\partial y} \beta + \frac{\partial \phi}{\partial z} \gamma$$

$$\frac{d\phi}{ds} = \frac{\partial \phi}{\partial x} \cos \alpha + \frac{\partial \phi}{\partial y} \cos \beta + \frac{\partial \phi}{\partial z} \cos \gamma$$

$$\frac{d\phi}{ds} = \frac{\partial \phi}{\partial x} \alpha + \frac{\partial \phi}{\partial y} \beta + \frac{\partial \phi}{\partial z} \gamma$$

$$\frac{d\phi}{ds} = \frac{\partial \phi}{\partial x} \alpha + \frac{\partial \phi}{\partial y} \beta + \frac{\partial \phi}{\partial z} \gamma$$

$$\frac{d\phi}{ds} = \frac{\partial \phi}{\partial x} \alpha + \frac{\partial \phi}{\partial y} \beta + \frac{\partial \phi}{\partial z} \gamma$$

$$\frac{d\phi}{ds} = \frac{\partial \phi}{\partial x} \alpha + \frac{\partial \phi}{\partial y} \beta + \frac{\partial \phi}{\partial z} \gamma$$

Directional Derivative of a Vector Field

$$\frac{Y_1}{Y_n} = f(F_n, M^0, \phi_1)$$

#### Geometry IV

##### Two-Dimensional Semicircular Arch Bridge Constrictions with Eccentricity:

The geometric characteristics were as follows:

- |                              |                       |                        |
|------------------------------|-----------------------|------------------------|
| a) $\frac{L}{b} = 0$         | d) $\phi_2 = 0^\circ$ | g) $e$ is a variable   |
| b) $\frac{bL_d}{A_{n2}} = 0$ | e) $\beta = 0$        | h) $F_n$ is a variable |
| c) $\phi_1 = 90^\circ$       | f) $N = 1$            | i) $M^0$ is a variable |

And the equation (3-10-1) can be reduced to:

$$\frac{Y_1}{Y_n} = f(F_n, M^0, e)$$

#### Geometry V-a

##### Two-Dimensional Semicircular Arch Bridge Constrictions with Skew:

The geometric characteristics were as follows:

- |                              |                        |                        |
|------------------------------|------------------------|------------------------|
| a) $\frac{L}{b} = 0$         | d) $O_2$ is a variable | g) $e = 0$             |
| b) $\frac{bL_d}{A_{n2}} = 0$ | e) $\beta = 0$         | h) $F_n$ is a variable |
| c) $\phi_1 = 90^\circ$       | f) $N = 1$             | i) $M^0$ is a variable |

And the equation (3-10-1) can be reduced to:

$$\frac{Y_1}{Y_n} = f(F_n, M^0, \phi_2)$$





Geometry V-bThree-Dimensional Semicircular Arch Bridge Constrictions with Skew:

This geometry is the same as the previous one, except that the length of the constriction is allowed to vary, the parameter  $\frac{L}{b}$  is thus a variable and the dimensionless equation (3-10-1) can be simplified to:

$$\frac{Y_1}{Y_n} = f(F_n, M', \phi_2, \frac{L}{b})$$

Geometry VIThree-Dimensional Two-Span Semicircular Arch Bridge Constrictions:

The geometric characteristics were as follows:

- |                              |   |
|------------------------------|---|
| a) $\frac{L}{b} = 0.50$      | f) $N = 2$ , Two-span case                  |
| b) $\frac{bL_d}{A_{n2}} = 0$ | g) $e = 0$                                  |
| c) $\phi_1 = 90^\circ$       | h) $F_n$ is a variable                      |
| d) $\phi_2 = 0^\circ$        | i) $M'$ is a variable                       |
| e) $\beta = 0$               | j) $p = \frac{b}{10}$ (for submerged tests) |
|                              | $p = \frac{b}{3}$ (for free surface tests)  |

The equation (3-10-1) can be reduced to:

$$\frac{Y_1}{Y_n} = f(F_n, M')$$

Geometry VIITwo-Dimensional Segment Arch Bridge Constrictions:

The geometric characteristics were as follows:

- |                              |                          |
|------------------------------|--------------------------|
| a) $\frac{L}{b} = 0$         | e) $\beta$ is a variable |
| b) $\frac{bL_d}{A_{n2}} = 0$ | f) $N = 1$               |
| c) $\phi_1 = 90^\circ$       | g) $e = 0$               |
| d) $\phi_2 = 0^\circ$        | h) $F_n$ is a variable   |

Formal Logic and the Law

1. The Law of Identity

2. The Law of Contradiction

3. The Law of Excluded Middle

4. The Law of Syllogism

5. The Law of Double Negation

6. The Law of De Morgan

7. The Law of Implication

$$p \rightarrow q \equiv \neg p \vee q$$

$$p \rightarrow q \equiv \neg(p \wedge \neg q)$$

$$p \rightarrow q \equiv \neg q \rightarrow \neg p$$

$$p \rightarrow q \equiv \neg q \rightarrow \neg p$$

i)  $M^0$  is a variable

Hence, equation (3-10-1) reduces to:

$$\frac{Y_1}{Y_n} = f(R_n, M^0, \beta)$$





## BIBLIOGRAPHY OF CHAPTER III

1. Birkhoff, G., "Calculation of Potential Flow with Free Streamlines", ASCE, Jour. Hydr. Div. Vol. 87, HY6, November, 1961.
2. Bakhmeteff, B. A., "Hydraulics of Open Channels", McGraw-Hill, 1932.
3. von Misses, R., "Berechnung von Ausfluss und Weirfallzahlen", Zeitschrift VDI, Vol. 61, 1917, p. 447.
4. Wu, I. P., "Preliminary Study of the Indirect Determination of Flood Discharge from Contracted Bridge Openings and High Water Marks", Memorandum from I. P. Wu to Mr. J. I. Perrey, Indiana Flood Control and Water Resources Commission, August 15, 1962.
5. Henry, H. R., Discussion on "Submerged Jets", Transactions ASCE, Vol. 115, 1950, p. 687.
6. Henry, H. R., Discussion on "Open Channel Constrictions", Transactions ASCE, Vol. 120, 1955, p. 1013.
7. Stevens, J. C., "Flow Through Circular Weirs", Journal of the Hydraulics Division, ASCE, Vol. 83, No HY6, December 1957.
8. Izzard, C. F., "Discussion on Open Channel Constrictions", Trans, ASCE, 1955, Vol. 120, p. 985.
9. Bradley, J. N., "Hydraulics of Bridge Waterways", U. S. Bureau of Public Roads, U. S. Government Printing Office, August, 1960.
10. Valentine, "Flow in Rectangular Channels with Lateral Constriction Plates", La Houille Blanche, Jan. - Feb. 1958, p. 75.
11. Lui, H. K., Bradley, J. N., Plate, E. J., "Backwater Effects of Piers and Abutments". Civil Engineering Section, Colorado State University, Fort Collins, Colorado, Rept. CER57HKL10, Oct. 1957.



## IV PRELIMINARY INVESTIGATION

A preliminary investigation was conducted in a small flume for the purpose of evaluating the design requirements for a larger testing flume and of establishing the testing procedure. The small flume also provided a facility where some preliminary tests could be run with scales and relative roughnesses different from those used in the large flume.

IV-1 Small Flume, Models and Test Conditions

For the purpose of preliminary testing, a small variable slope flume 6" wide and 12' long was used. The channel sides and bottom were constructed of lucite and carefully aligned by means of adjusting screws. (Fig. 4-1) The slope of the flume was controlled by a hand operated scissor jack at the lower end of the flume. An aluminum I-beam mounted horizontally above the flume served as a track for the mechanical and electric point gages used in obtaining the water surface measurements. The electric point gage consisted of two metal points of slightly different length that were wired to a set of batteries and a galvanometer. When the shorter metal point would make contact with the water surface, the longer one being already submerged, the circuit would close and the galvanometer would deflect. The flow was metered by a 1 inch orifice plate in a 2 inch supply line. Two and three dimensional tests were run with both smooth and rough boundaries. For the rough tests, the bottom and the walls were lined with copper wire mesh of 16 meshes per inch.

The two dimensional semicircular models were constructed with diameters of 3, 4 and 5 inches (see fig. 4-2). The material used was brass. The edges were machined to 1/32 of an inch and then beveled to a 45 degree angle. The two dimensional segment models were of the same type of construction as the semicircular models and had a value of  $\eta = d/r$  equal to 0.5. Three three-dimensional models were built for the purpose of this preliminary testing.





The material used was "Lucite". The dimensions of the three-dimensional models are the following:

Lucite Model	Length of Model Along Stream in Inches	Arch Diameter in Inches	Rise Inches
1	9.7	7.7	1.4
2	24	5	2.5
3	24	4	2

A photograph of the models is given in Figure 4-2. Model No. 1 is a reproduction to a scale of 1/60 of the Arch Bridge in Clay County, Indiana, on State Road 246e over Branch Connley Ditch. For measuring the water surface under the bridge, vertical glass tubes were installed on the models as shown in Figure 4-4. Through these tubes the probe of an electrical point gauge could be introduced.

In all cases, an adjustable weir was used at the end of the flume. This permitted to increase the depth of flow, and to reduce the length of the M-2 curve at the free overfall so as to obtain a long test section with uniform flow. The weir height varied for the different tests. The weir heights used are indicated for the several tests.

The three-dimensional model tests were conducted for the following variable conditions:

1. Wall roughness: The channel sides and bottom were either smooth or rough, as described in the previous paragraph.
2. Slope: Three different slopes were used:  $S_0 = 0$ ,  $S_0 = 0.0003$ ,  $S_0 = 0.0005$ .
3. Discharges: The discharges used in cubic feet per second are:
 

$Q = 0.0114$	(with 0.413 in orifice meter)
0.0138	"
0.015	"
0.017	(with 1.034 in orifice meter)
0.023	"
0.028	"
0.031	"
0.0379	"
0.042	"
0.0519	"
0.0525	"





4. Models: Three models were used, designated as Nos. 1, 2, 3 and as described in previous paragraphs.

The steps of the test routine were the following:

1. Adjustment of horizontality of beam on which the point gauges travel. This was done by maintaining a pool of water in the flume, and taking the point gauge readings of the water surface at several points. The beam position was adjusted so that the point gauge readings were the same all along the beam.
2. Control of the channel slope. This was accomplished by adjusting the scissor jack until the difference between the point gauge readings of the bottom of the flume at two points 10 feet apart would be equal to ten times the desired slope.
3. Establishment of the flow. The flow was adjusted by means of a control valve so as to obtain the desired reading on the orifice meter manometer. The desired readings were obtained from the calibration curves.
4. Establishment of uniform flow. The adjustable weir at the downstream end of the flume was set so as to obtain uniform flow through most of the flume. The flow was considered uniform in a reach when constant depths were observed in that reach. Depth was measured at one foot intervals. The section of the flume with uniform flow was the test section.
5. Installation of model in flume. The models were installed in the test section so as to show the complete regain curve and as much as possible of the back-water curve. In the case of the tests with rough channel walls, no roughness was installed on the model. The bottom of the flume under the arch was covered with artificial roughness for models 2 and 3 only. For model 1 the roughness was not installed on the bottom under the bridge, but was installed along the rest of the flume.

1. Installation of the pump  
The pump was installed in the basement of the building. The pump was connected to the main water line and the discharge pipe was connected to the sewer line. The pump was tested and found to be operating properly.

2. Installation of the float valve  
The float valve was installed in the main water line. The float valve was tested and found to be operating properly. The float valve was adjusted so that it would shut off the water when the tank was full.

3. Installation of the overflow pipe  
The overflow pipe was installed in the main water line. The overflow pipe was tested and found to be operating properly. The overflow pipe was adjusted so that it would discharge the water into the sewer line when the tank was full.

4. Installation of the vent pipe  
The vent pipe was installed in the main water line. The vent pipe was tested and found to be operating properly. The vent pipe was adjusted so that it would discharge the air into the atmosphere when the tank was full.

5. Installation of the cleanout  
The cleanout was installed in the main water line. The cleanout was tested and found to be operating properly. The cleanout was adjusted so that it would allow the water to be cleaned out of the tank when necessary.

6. Observation of the water surface profile. The water surface elevation was first measured with a mechanical point gauge along the center line of the flume upstream and downstream of the model. At a later time vertical glass tubes were installed on the models. The water surface elevation was then measured with an electrical point gauge along the centerline of the arch. The test data are tabulated in the Appendix. (Table 4-1)

6. Operation of the water surface profile. The water surface elevation was first measured with a mechanical point gauge along the center line of the flume upstream and downstream of the model. At a later time piezometer tubes were installed on the models. The water surface elevation was then measured with an electrical point gauge along the centerline of the flume. The test data are tabulated in the Appendix. (Table A-1)



## -2 Test Results

The observations of the water surface profiles observed are tabulated in Table of the Appendix.

Col. 1 is the station as read from the tape on the horizontal beam. The tape is graduated to .01 foot from downstream (station 4) to upstream (station 14).

Col. 2 is the distance along the flume in the direction of the flow. Station 14 corresponds to zero and station 4 to 10.

Col. 3 is the flume bottom point gauge reading. At each 1 foot or 2 foot interval the bottom elevation was observed with the mechanical point gauge.

Col. 4 is the water surface reading obtained with the mechanical point gauge before fixing the model, i.e., with uniform flow.

Col. 5 is the water surface reading upstream and downstream of the model obtained with the mechanical point gauge and the water surface under the bridge obtained with the electrical point gauge.

Col. 6 is the difference between Col. 4 and Col. 3, namely the normal water depth.

Col. 7 is the difference between Col. 5 and Col. 3, namely the depth of water with model in place.

Col. 8 is used for general remarks such as: slope, diameter, rise, length of model, tail weir height that were used in the particular set of readings were noted in this column.

The data pertaining to the rough boundary, two dimensional, segment arch tests the small flume and the calculations necessary for the analysis of the segment are given in Table 4-2.

The results of the two-dimensional weir tests were put in graphical form by plotting the coefficient of discharge vs the Froude Number with the channel width as the parameter. The channel width ratio  $M$  is defined as the ratio of the

The observations of the test results are given in Table 1 of the Appendix.

Table 1 is the table of the test results. The test results are given in Table 1 of the Appendix.

Table 2 is the table of the test results. The test results are given in Table 2 of the Appendix.

Table 3 is the table of the test results. The test results are given in Table 3 of the Appendix.

Table 4 is the table of the test results. The test results are given in Table 4 of the Appendix.

Table 5 is the table of the test results. The test results are given in Table 5 of the Appendix.

Table 6 is the table of the test results. The test results are given in Table 6 of the Appendix.

Table 7 is the table of the test results. The test results are given in Table 7 of the Appendix.

Table 8 is the table of the test results. The test results are given in Table 8 of the Appendix.

Table 9 is the table of the test results. The test results are given in Table 9 of the Appendix.

Table 10 is the table of the test results. The test results are given in Table 10 of the Appendix.

Table 11 is the table of the test results. The test results are given in Table 11 of the Appendix.

Table 12 is the table of the test results. The test results are given in Table 12 of the Appendix.

weir diameter  $b$  to the flume width  $B$ . This graph is shown in the upper left corner of Figure 4-5. The lower graph shows the relation of the Froude Number and the ratio of depth upstream of the weir to the normal depth.

A typical water surface profile for the three-dimensional arch bridge models is shown in Figure 4-5. In that case, the flume walls were lined with copper wire mesh of 16 meshes per inch. This gave a Manning's roughness coefficient of approximately 0.025, which is typical of many canals and natural streams. Figure 4-7 shows the results of the three-dimensional tests with smooth boundaries, using bridge models of width  $L = 24$  inches. The coefficients of discharge  $C_d$  and the ratio of the backwater depth  $Y_1$  to the normal depth  $Y_0$  are plotted vs the Froude Number for several values of the channel width ratio  $M$ . The results of the two- and three-dimensional tests with smooth boundaries are compared in Figure 4-8. It is interesting to notice that for small Froude Numbers, say less than 0.5,  $C_d$  and the ratios  $\frac{Y_1}{Y_0}$  are approximately the same for the two cases. For higher Froude Numbers, the three-dimensional tests exhibit smaller values of  $C_d$  and larger values of  $\frac{Y_1}{Y_0}$ .

As part of the preliminary testing, a series of 93 tests were run in the small flume on two dimensional segment weirs (Geometry VII) with a  $\eta = d/r$  value of 0.5 (See Table 4-2). The data obtained were reanalyzed in terms of the channel opening ratio  $M^1$ . These tests were run in the small channel with rough boundaries which had a Manning's  $n$  of 0.0201. Results were plotted in the same manner as the large flume rough tests and are shown in Figure 4-8a.





## V EXPERIMENTAL EQUIPMENT

### V-1 Design and Construction of the Testing Flume

Before the design of the flume itself could proceed, it was necessary to determine whether the backwater and regain phenomena could be represented to a convenient and easily measurable scale in the space available in the hydraulics laboratory.

Several sets of arch bridge plans provided by the Indiana State Highway Department were analyzed for the values of backwater. The theory of varied flow and the equations and tables presented by Bakmeteff<sup>(1)</sup> and by the U.S. Bureau of Public Roads<sup>(2)</sup> were used. It was possible to make only an approximate calculation of the backwater because of the unknown effect of an arch-type constriction.

One criterion for the selection of the flume size was that it had to be sufficiently long to accommodate the full length of the regain curve downstream of the constriction, the bridge width and part of the backwater curve upstream of the constriction within the test section of the flume. The test section of the flume includes only that part of the flume where uniform flow can be obtained. The upstream end of the flume, where the flow is developing, and the downstream end which is affected by the curvature of the free surface are not suitable for testing. The limitations on the flume size were imposed by the space available and by the capacity of the water supply.

A calculation was made for bridge S79 in Clay County in Indiana. This bridge has a span of 30 feet and the stream has a width of 46 feet. The backwater curve and the regain curve were calculated assuming a velocity of 6 ft/sec in the constriction. The prototype bridge had a width of 48 feet and the calculated length of the regain curve was 146 feet. At a scale of 1:10 this would represent a length of 19.4 feet. In a test section of 30 feet in length, it would be possible to reproduce a 10 foot section of the upstream backwater.





Taking into account the boundary layer growth at the entrance of the flume and the drop-off curve at the downstream end, a total length of about 60 feet was required. A width of 5 feet and a depth of 2 feet was consistent with the scale of 1/10 for this bridge crossing. These flume dimensions required a pumping capacity which was close to the maximum supply available of 2100 GPM.

From this and similar computations and from the small flume tests, <sup>(1)</sup> it appeared that a flume length of 64 feet utilizing all of the available space in the laboratory would be satisfactory.

The width of the flume was fixed at 5 feet. This was based on a consideration of the scale ratios and the space available. The cross section of the flume was to be rectangular since this configuration lent itself well to both ease of construction and adaption.

In order to test the flows under varying slope conditions, the flume was to be tiltable about one end. Screw jacks were selected for the slope control because of accuracy and ease of operation, as well as permanence and appearance.

In order to keep the deflections due to the variable weight of water within the same order of magnitude of the smallest readings of the point gage for depth measurement, 0.1 mm, the flume bottom was designed of 1/4 inch steel plate supported at 2 foot intervals on channels. The channels in turn were to be supported by two main beams riding on the jacks. The side plates were designed of 1/4 inch steel plate supported by vertical angles resting on the channel members. A longitudinal horizontal angle mounted on the vertical angles served as a support for the guide rails. The guide rails, which serve as a reference plane from which measurements are based, were to be polished stainless steel to minimize corrosion and scale.

The design was based on a possible water depth of 2 feet. The distance between beam supports was set as 20 feet. Simply supported connection was assumed. The beams were selected so that their deflections would be negligible. The beam first selected

Testing into account the boundary layer growth at the entrance to the flame tube  
top-off curve at the downstream end, a total length of about 50 feet was provided  
th of 2 feet and a depth of 2 feet was considered with the scale of 1/10 inch  
ridge crossing. These three dimensions required a trapping capacity which  
to the maximum supply available of 2000 GPM.  
Three this and similar considerations and three separate flame tubes (2) and (3)  
a flame length of 40 feet allowing all of the available space in the tube  
be satisfactory.  
The width of the flame was fixed at 2 feet. This was fixed on a number  
scale ratios and the space available. The space available at the flame was  
tangential since this configuration itself itself will be set, some of space  
and adaption.  
In order to test the flame under varying pipe conditions, the three tubes were  
the about one end. Seven feet were selected for the three tubes, and  
up and ease of operation, as well as convenience and space.  
In order to keep the deflection due to the variable weight of the tubes  
order of magnitude of the weight of the tubes, the tubes were  
0.1 in, the flame tubes were designed at 1/10 inch steel plate thickness  
intervals on channels. The channels in this case were to be spaced  
riding on the jacks. The side plates were designed at 1/10 inch steel plate  
ted by vertical angles resting on the channel supports. A jack, used at the  
angles mounted on the vertical angles moved as a support for the tubes.  
the rails, which serve as a reference plane from which measurements are  
to be polished stainless steel to avoid corrosion and scale.  
The design was based on a possible water depth of 2 feet. The distance  
supports was set at 30 feet. Slightly spaced connection was assumed. The  
affected so that their deflections would be negligible. The beam fixed between



was an 18 I 54.7 which gave a calculated deflection of 0.00225 feet under the design loading. Contacts with the fabricator and erector were made at a later date and it was found that a 20 I 65.4 would be available at a cost less than that of the lighter beam. The use of the heavier beam was accepted and the design proceeded based on this beam. The deflection due to the variable water weight was approximately 0.002 feet for a depth of one foot. Adjustment bolts were provided for transverse leveling. These adjustment bolts were placed between the channels and the main beams. This arrangement gave the bottom plate full support across its width at 2 foot intervals.

The bottom plate was designed slightly wider than the flume width. This permitted attaching an angle to hold the bottom edge of the vertical plate fixed. The upper edge of the vertical plate had nuts welded on at the two foot points. Studs were attached between the nuts and the vertical angles to support the plate and provide an adjustment for its longitudinal alignment. The inside of the flume was finished with an epoxy resin applied with a hand roller. The flume construction is shown in figure 5-1.

#### Tailgate

Control over the depth was exercised by a gate mounted at the end of the flume. The gate was manually operated from the side of the flume. Figure 5-3 shows the gate. The gate was made in such a way that it could be used either as a sluice or as a weir. Throughout the tests, the gate was used exclusively as a weir.

#### Forebay

The forebay, 8 feet wide and 10 feet long, was constructed of plywood and lined with sheet metal, and is shown in figure 5-4. The 3 inch and 6 inch pipes entered the rear of the forebay at the top. The 6 inch line was centered and the 3 inch line was placed slightly off center. The diffusing mechanism for each supply line consisted of a tee and cross pipe of the same size as the line at the bottom of the forebay. The turbulence level of the entering water was controlled by a 4 inch gravel baffle and three wire mesh screens of 13 mesh per inch. The transition section continuing





into the bottom and side walls of the flume was made of quarter ellipses in the horizontal and vertical planes respectively with a ratio of major to minor axes of 1.5 to 1.0. The joint between the flume and the forebay was sealed with a flexible rubber gasket mounted so as not to interfere with the flow.

### Slope Control Mechanism

The flume rests upon six screw jacks and a hinge. The hinge is located at the joint of the flume and the forebay. The jacks are similar in all respects with the exception of the gear ratio. The jacks are divided into three pairs with rates of raise of one, two, and three inches for 96 turns of the shaft. Since the hinge was a fixed point and the opposite end of the flume was the point of maximum movement, the jacks were arranged such that the pair nearest the hinge moved the least and the pair at the opposite end of the flume had largest displacement per revolution. This maintained the bottom of the flume as a plane while it was being raised and lowered. The jacks on each side of the flume were driven by a common 1 inch shaft line connected at one end to a 90° miter gear. The miter gears on either side in turn were connected to a single 60:1 ratio gear reducer. The power to operate all the jacks was supplied by a 1-1/2 horsepower, 1750 revolutions per minute, reversible, electric motor connected directly to the gear reducer. This provides a rate of vertical displacement at the downstream jack station of approximately 1 inch per minute.

The jacks were arranged in such a way that the downstream end of the flume may move from 12 inches below horizontal to 3 inches above horizontal, resulting in a maximum positive slope of 1/60 and a maximum adverse slope of 1/240. The motor was controlled by a raise, lower, and stop control switch. Safety switches were located both near the motor and near the control switch. It was necessary to unlock these before the control circuit could be completed. In addition, automatic limit switches were provided to prevent running the jacks beyond their limits. The general arrangement of jacks and gears is shown in figure 5-5.



In order to connect the ends of the jacks (which move in a vertical line) to the flume (which moves in an arc), it was necessary to use a pinned linkage. A photograph of the linkage is shown in figure 5-2. (Appendix C) Due to the arc of the linkage, the relation between the rise of the flume and the revolutions, turned by the jack shafts, was not linear. Therefore, it was necessary to make a calibration of the slope rather than computing it.

At the time of erection, the jacks were leveled at .001 foot before the flume was erected. During the alignment procedure, the jacks were raised or lowered individually as needed to obtain a level base. The shaft couplings were then installed and no further individual movements were made.





## V-2 Water Supply and Measurement System

The water available in the laboratory is recirculated through the system by two pumps rated at 300 Gpm and 2000 Gpm. This 3 inch line contained a 3 x 2.25 inch venturi accurate to 0.5% over the range from 30 Gpm to 300 Gpm. A 60 inch differential manometer reading to 0.01 inch was connected to the venturi and filled with tetrabromoethane (specific gravity 2.95) which gave a manometer deflection of 51 inches with a flow of 336 Gpm.

The 2000 Gpm pump was connected to a 6 inch line which contained a 6 x 4.176 inch venturi accurate to 0.5% over the range 200 Gpm to 2000 Gpm. A 30 inch differential manometer reading to 0.01 inch was connected to the venturi and filled with mercury (specific gravity 13.6). This manometer gave a deflection of 14.9 inches for a maximum flow of 1790 Gpm. In both cases the venturis were fitted with air vents to insure proper measurements.

In order that the calibration of the venturi meters should have no error larger than that of the venturi meter, the scale to be used for the calibration was checked against standard weights by the Indiana State Board of Health, Division of Weights and Measures. The scale error was less than 0.2% or 2 pounds per 1000 pounds. For the purpose of calibrating of the venturi meters, branch lines led to a baffled concrete channel located above the weighing tank.

At the point immediately before the 3 inch and inch lines entered the forebay, valves and valve bypasses were installed. The 6 inch line had a 2 inch bypass and valve and the 3 inch line was fitted with a 1 inch bypass and valve. The manometers were mounted in a position easily visible to the person adjusting the valves. The overall apparatus arrangement in the laboratory is shown in figure 5-4.

The calibration curves of the venturi meters are given in figures 5-6 and 5-7.





### V-3 Measuring Equipment

#### a) Instrument Carriage

An aluminum instrument carriage, mounted on two stainless steel guide rails running the length of the flume, was installed so that the bottom of the flume could serve as a reference plane. The four wheels of the carriage were grooved to give a precision fit on the rails. One of the wheels had a set screw to keep the carriage from moving when an experiment was conducted. A surveyors tape was mounted along the whole length of the flume and an indicating point on the carriage served as a reference point for all longitudinal measurements. Another surveyors tape was installed in the transverse direction of the flume on a grooved rail of the instrument carriage. This rail served as a guide for the slide on which a point gage and Prandtl tube were mounted. This slide also had an indicating point serving as reference point for transverse measurements. By means of these two tapes any point in the flume could be located in the horizontal plane. The instrument carriage was also equipped with a fluorescent lamp, several electrical outlets and a wide 3/4 inch plywood strip on one side to serve as a desk for notekeeping etc. The carriage could easily be moved to any location along the flume and locked in a specific position with an accuracy of 0.005 ft. (Figure 5-8 shows a top view of the carriage.)

#### b) Point Gage

All water surface elevation measurements were obtained by means of an electric indicating point gage. It was mounted on the instrument carriage slide which could be positioned with an accuracy of  $\pm 0.002$  ft. in the transverse direction of the flume. The staff of the point gage was marked in millimeters and was equipped with a vernier which allowed a reading accuracy of  $\pm 0.05$  mm in the vertical direction. The accuracy of the water surface elevation measurements varied between 0.1 mm to 2.0 mm depending on the smoothness of the free surface.



### c) Prandtl Tube

The flow velocity measurements were obtained by means of a 1/8" O.D. Prandtl tube of standard design. The Prandtl tube was mounted on a vertical staff which was marked in 0.2 cm and had a vernier allowing a vertical positioning within  $\pm 0.01$  cm of accuracy. A set screw prevented the position to change during test measurements. The support of the Prandtl tube permitted, in addition to vertical and traverse motions, a rotation so that the horizontal portion of the probe could be aligned according to the direction of the flow indicated by a freely swinging stiffened tuft attached to the tube. The amount of rotation was measured as an angle by means of an indicator sliding along a fixed protractor. For measurement of large velocities, the Prandtl tube was connected to an inverted U manometer which had a fluid of specific gravity 0.810.

### d) Variable-Reluctance Pressure Transducers

The small magnitude of the pressure differentials to be measured with the Prandtl tube in zones of small velocities made it necessary to employ a Variable-Reluctance Differential Pressure Transducer (model P7D, Pace Eng. Comp.) instead of the conventional liquid manometer. In the low velocity regions a pressure transducer having a range of  $\pm 0.1$  psid. was used. In the higher velocity regions - as in the discharge at of the models - range at  $\pm 0.5$  psid. was needed. Figure 5-10 shows sketch of velocity pressure transducer system.

### e) Calibration of Velocity Probe

By using the relation between the dynamic and static head  $\frac{V^2}{2g} = h$  (where V is velocity in fps., h is feet of water and g is the acceleration of gravity) a static calibration could be performed.

Two reservoirs were connected to the stagnation and static openings of the Prandtl tube respectively. The reservoirs were connected through a valve. A datum level was measured by an electric point gage when the connecting valve was open, and the voltmeter needle was adjusted to the zero mark. The pressure was then equal on both sides of the diaphragm in the pressure transducer. The valve connecting the reservoirs was closed







and distilled water was added to increase the level in the reservoir connected to the stagnation opening. The water level was recorded for even increments in the voltmeter reading. Figure 5-11 shows the calibration setup. Calibration curves are shown in Figure 5-12.



#### V-4 Boundary Roughness Analysis in the Large Flume

##### a) Smooth Boundaries

The actual testing program in the large flume was run under two different boundary roughness patterns. The first roughness which will be referred to as the smooth boundary consisted of the steel flume walls finished with an epoxy resin paint.

It was necessary to define the region of uniform flow prior to testing the models so that their effects on the flow pattern could be evaluated. The models and the affected flow reach must be contained within a uniform flow region. Special tests were run to determine the characteristics of uniform flow. The values of Manning's  $n$ , the Darcy-Weisbach friction coefficient and the length required for the full boundary layer development were calculated as discussed below.

The section used for model testing was the portion of the flume between 20.00 ft. and 50.00 ft. from the entrance. With the known uniform depth within the test equation, the discharge, channel geometry and slope, the Manning's equation could be used to determine a value of Manning's  $n$ . Throughout the testing program, it was felt necessary to maintain good control of uniform depths. Based upon an average of all the calculations of Manning's  $n$  for the smooth boundaries, a value of 0.0110 was determined. The range of  $n$  was from 0.009 to 0.0130 for discharges and Froude numbers from 1 cfs to 4 cfs and 0.05 to 1.00 respectively.

##### Darcy-Weisbach Coefficient

In addition, the Darcy-Weisbach friction factor was calculated according to the following equation.

$$f = 8 g R_n S / V_n^2 \quad (5-4-1)$$

where

$f$  - Darcy-Weisbach friction factor

$V_n$  - Average velocity

$R_n$  - Hydraulic radius

$S$  - slope



The friction factor was plotted against the Reynolds number and compared to the Blasius and Prandtl Von-Karman curves for smooth surfaces. The resulting plot is shown in figure 5-13. The Reynolds number is that defined by Chow<sup>(3)</sup> as  $VR/\nu$ , where  $\nu$  is the kinematic viscosity of the water. Some of the scatter of the smooth data points is due to the fact that the surfaces were so smooth that relatively flat slopes were necessary. As a result, the slopes and surface profiles were very difficult to measure and they introduce experimental errors in the calculations.

#### Turbulent Boundary Layer Growth

To ensure that the model tests were being run in a regime of fully developed turbulent flow, the distance downstream from the entrance of the flume to the point at which the boundary layer thickness  $\delta$  was equal to the normal depth  $y_n$  was computed. The equation used for the development of the turbulent boundary layer for smooth surfaces was that developed for flow over a flat plate. This equation is based upon the Blasius  $1/7$ th power law. (See for example Daugherty and Ingersoll<sup>(4)</sup>)

$$\delta/X = 0.377 / Re_X^{1/5} \quad (5-4-2)$$

where

$\delta$  = the thickness of the turbulent boundary layer

$X$  = distance downstream from the point where  $\delta = 0$

$$Re_X = V_n X / \nu$$

$V_n$  = average uniform velocity

Solving (27) for  $X$

$$X = (\delta / 0.377)^{5/4} (V_n / \nu)^{1/4} \quad (5-4-3)$$

Although this formula is restricted to flow over a flat plate, it will serve as a first approximation in the problem at hand. If  $\delta$  is made equal to the uniform depth  $T_n$ , then the value of  $X$  will estimate the distance to the point at which the turbulent boundary layer becomes fully developed.

Test results showed that the values of  $X$  ranged from about 8 feet for small discharges and steep slopes to about 40 feet at high discharges and steep slopes.





For the majority of the runs, the values of  $X$  were well within the first 20 feet of the flume, indicating that the flow could be considered fully developed within the test section.

#### b) Rough Boundaries

It has been shown that Manning's  $n$  value for the smooth boundaries was 0.0110. This value was not representative of any natural stream condition. It was decided to run a second series of tests with a boundary roughness which would simulate a more natural condition, and would permit the use of steeper slopes in the flume.

For natural streams, Daugherty and Ingersoll<sup>4</sup> give the following values of Manning's  $n$ .

	Minimum $n$	Maximum $n$
Smooth Natural Streams	0.025	0.033
Roughest Natural Streams	0.045	0.060

Based upon a scale ratio of 1/10 between model and prototype, a roughness with  $n = 0.020$  in the model would correspond approximately to an  $n = 0.030$  in a natural stream. Also a Manning's  $n$  of 0.030 in the model would be approximately 0.045 in the field. Therefore, it would be desirable to select a roughness pattern for model testing purposes that would have a Manning's  $n$  between 0.020 and 0.030.

Referring to the work done at Colorado State University<sup>5</sup>, the following roughness pattern was selected. The roughness along the bottom consisted of two layers of 1/4 inch aluminum rods; a bottom layer of longitudinal bars placed 12 inches on center and a top layer of transverse bars 6 inches on center. Along the side walls, there was one layer of vertical bars 6 inches on center placed 1/4 inch from the wall. The bottom layers of bars were tied together with screen wire. The vertical bars were tied at the bottom to the transverse bars and clamped to the walls above the free surface. This roughness pattern can be seen in figure 5-14.

Figure 5-15 is a diagram of two velocity profiles. One profile was taken 0.03 feet downstream of a roughness element and the other at a point midway between two



adjacent bars. It may be concluded that a significant amount of flow was beneath the elements.

#### Manning's n and Darcy-Weisbach f

As in the case of the smooth boundaries, several uniform flow tests were made. The tests were conducted for discharges of 1, 2 and 3 cfs and for 24 different slopes ranging from 0.000010 to 0.00450. Results show that the Froude numbers ranged from 0.05 to 0.56. An average value of Manning's n was computed as 0.0238. The actual value of n ranged from 0.022 to 0.025.

Darcy-Weisbach friction factors were calculated for the rough boundaries and plotted in figure 5-13. The data for rough boundaries was broken down according to constant discharge and constant hydraulic radius. The raw data for the 24 normal depth tests in the rough channel are listed in table 5-1 of the Appendix.

#### Equivalent Sand Roughness

Nikuradse's equivalent sand roughness was determined from an equation given by Chow<sup>3</sup> for uniform flow in rough open channels. (page 204)

$$V_n = V_f (6.25 + 5.75 \log (R_n/k)) \quad (5-4-4)$$

where

$V_n$  = average uniform velocity

$V_f = \sqrt{g R_n S}$  = shear velocity

$R_n$  = hydraulic radius

$k$  = Nikuradse's equivalent sand roughness

Results showed the average  $k$  to be 0.095 ft. with a range from 0.05 ft. to 0.12 ft.

#### Turbulent Boundary Layer Growth

As for the smooth boundary, the growth of the turbulent boundary layer was investigated. For the rough flow, an approximate method proposed by Bauer and presented in Chow<sup>4</sup> (page 198) was used. Although this method was primarily developed for steep slopes, it was found applicable to channels of small slope provided the flow was uniform. The equation proposed by Bauer was





$$\delta/\lambda = 0.024 / (\lambda/k)^{0.13}$$

(5-4-5)

where

 $\delta$  = thickness of the turbulent boundary layer $\lambda$  = distance from the point where  $\delta = 0$  $k$  = Nikuradse's equivalent sand roughness

Having already evaluated  $k$  for the rough boundaries, the distance to the point where the boundary layer thickness was equal to the normal depth  $Y_n$  could be evaluated. For the maximum depth, the value of  $\lambda$  determined from equation 5-4-5 was 80 feet. However, for the majority of tests, the value of  $\lambda$  was equal to or less than 25 feet, in which cases the flow was fully developed in the test section.

Sayre and Albertson<sup>7</sup> have presented a comprehensive report on the effect of roughness elements in rigid open channels. They state that a roughness parameter  $\chi$  (chi) which depends "on the size, shape and spacing of the roughness elements", should completely describe the boundary roughness. The true value of  $\chi$  depends on whether or not 1) the boundary is hydrodynamically rough -- negligible viscous effects, and 2) the channel is sufficiently wide such that any appreciable side wall effects are essentially eliminated.

According to Robinson, Koloseus and Sayre, the friction coefficient for fully rough turbulent flow may be expressed as a function of the relative roughness and a parameter representing the roughness spacing. In terms of Chezy  $C$ , as given by Sayre and Albertson<sup>7</sup>

$$C / \sqrt{g} = A \log (Y_n/a) + C_2$$

(5-4-6)

$C_2$  = a roughness parameter representing the roughness spacing and independent of roughness size.

$a$  = parameter describing the actual roughness height

$A$  = slope of the plotted line

The constant  $C_2$  may be found by graphical extrapolation in a  $C/\sqrt{g}$  vs  $Y_n/a$  plot as the value of  $C/\sqrt{g}$  at which  $Y_n/a = 1$ . The value of  $Y_n$  extrapolated to  $C/\sqrt{g} = 0$  defines the roughness parameter  $\chi$ . The properties of  $a$  and  $C_2$  in equation (5-4-6) are com-

where

$z$  = distance of the point from the origin

$r$  = distance from the point to the origin

$k$  = Wigner's constant

Having already obtained the value of  $k$  from the data of the first experiment, we can now calculate the value of  $k$  from the data of the second experiment.

where the boundary layer thickness is denoted by  $\delta$ .

For the second experiment, the value of  $k$  is found to be 0.025.

However, for the purpose of the present study, the value of  $k$  is taken to be 0.025.

In which case the value of  $k$  is found to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

which denotes the value of  $k$  for the second experiment.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

Since the value of  $k$  is found to be 0.025, the value of  $k$  is taken to be 0.025.

combined in  $\chi$  according to the relationship

$$C_2 = -A \log (\chi / a) \quad (5-4-7)$$

Sayre demonstrated that by describing the boundary roughness by a single parameter the data would group about a single curve described by the equation

$$C / \sqrt{g} = 6.06 \log (Y_n / \chi) \quad (5-4-8)$$

Extensive comparisons to the work of Sayre and Albertson were made. Since the true value of  $\chi$  depends on having fully rough flow, the testing flume was set to its maximum slope of 0.0125 and a series of six tests at various discharges were run. The data for these tests are given in Table 5-2 of the Appendix.

Figure 5-16 shows a plot of the resistance function  $C/\sqrt{g}$  against the value of  $\log Y_n/a$  in equation (5-4-6). This plot was made by assuming the value of  $a$  to be  $1/2$  inch for the particular pattern of  $1/4$  inch aluminum rods. The value of the slope was 6.06 as in equation (5-4-8) and the extrapolated value of  $C_2$  was 3.15. With the values of  $C_2$ ,  $A$ , and  $a$  the value of  $\chi$  was determined to be 0.0126 feet. Figure 5-17 gives a plot of equation (5-4-8). The determined  $\chi$  value was used to plot this curve.

#### Velocity Distribution

Sayre also demonstrated that equation (5-4-8) can be used to represent velocity profiles. The resistance function  $C/\sqrt{g}$  is equivalent to  $V_n/\sqrt{\tau_o/\rho}$  where the shear velocity  $\sqrt{\tau_o/\rho}$  is equal to  $\sqrt{g Y_n S}$  for open channel flow. Along with the normal depth tests to determine the  $\chi$  parameter, a centerline velocity profile was taken at slope of 0.0125 and a discharge of 3.714 cfs. The profile is shown in dimensionless form in figure 5-18. It is compared to the similar profile presented by Sayre. The equation obtained was

$$v / \sqrt{\tau_o/\rho} = 6.06 \log (y/\chi) + 4.6 \quad (5-4-9)$$

The noticeable difference in the constants (i.e. 4.6 and 2.6) was probably due to the different type of roughness used. The roughness baffles used by Sayre were placed in such a way that there was no flow beneath the elements. The numerical value of

used in  $\chi$  according to the relationship

$$G^2 = -\lambda \log (\chi^2 / n)$$

are demonstrated that by describing the frequency spectrum of the data would group about a single curve described by the equation

$$G^2 (\sqrt{E} - \sqrt{E_0})^2 = \chi^2 / n$$

Extensive consideration to the form of the data and the values of  $\chi$  have shown that the data from the various channels slope at different rates and that the data for these levels are not in the same plane.

Figure 2-10 shows a plot of the data for the various channels. The data for the various channels are shown for the various levels of the data. The data for the various channels are shown for the various levels of the data. The data for the various channels are shown for the various levels of the data.

Figure 2-11 shows a plot of the data for the various channels. The data for the various channels are shown for the various levels of the data. The data for the various channels are shown for the various levels of the data. The data for the various channels are shown for the various levels of the data.

$$\sqrt{E} - \sqrt{E_0} = G^2 / \chi^2$$

noticeable difference in the data for the various levels of the data. The data for the various channels are shown for the various levels of the data. The data for the various channels are shown for the various levels of the data.



a in equation (5-4-6) was assumed to be 1/2 inch. In actuality an effective value of a less than the assumed value could probably have been used. If a smaller value of a less than 1/2 inch had been used, then the value of  $\chi$  would decrease and the numerical values of  $y/\chi$  in figure 5-18 would increase causing the velocity profile to shift to the left. The constants would then be approximately equal.

#### General Resistance Diagram

Figure 5-19 shows a portion of the general resistance diagram for uniform flow in rigid open channels as presented by Sayre. The equations shown are those derived in his original paper. Added on this graph are the six special tests for rough boundaries and the value corresponding to the uniform flow depths used in both the smooth and rough boundary model testing program. In a later section of this report, the concepts presented in the paper of Sayre and Albertson have been extended to apply to field conditions. Although their work pertained only to rigid open channels, it is shown that the  $\chi$  parameter could possibly be applied to natural rivers and streams.





## BIBLIOGRAPHY OF CHAPTER V

1. Bakmeteff, B. A., "Hydraulics of Open Channels", Engineering Societies Monograph", McGraw-Hill, 1932.
2. U. S. Bureau of Public Roads, "Computation of Backwater Caused by Bridges", October, 1958.
3. Chow, Ven te, "Open Channel Hydraulics", McGraw-Hill, 1959.
4. Daugherty, R. L., and Ingersoll, A. C. "Fluid Mechanics", McGraw-Hill, 1954.
6. Liu, H. K., Bradley, J. N., Plate, E. J., "Backwater Effects of Piers and Abutments", Colorado State University, Report CER-57-HKL-10, October, 1957.
10. Sayre, W. W., and Albertson, M. L., "Roughness Spacing in Rigid Open Channels", Trans. ASCE, 1963, Vol. 128, Part I, p. 343.



## VI PROCEDURE AND DATA PROCESSING FOR FREE SURFACE FLOW TESTS

VI-1 Selection of Variables

For each geometry, several models were built to cover the practical range of the geometric and flow variables. The principal geometric variable is  $M = b/B$ . Models were built to cover 3 to 5 different values of  $M$ . A listing of the range of all the geometric variables tested for the seven basic geometries is given in the table, page 93.

The principal flow variable that was varied was the Froude number. Tests were generally made for a range of values of the Froude number between 0.1 and 0.5. Each value of the Froude number could be obtained with different values of the discharge. The discharges used varied between 1 and 4 cfs.

Once the Froude number and the discharge were selected, the normal depth, the tail gate elevation and the flume slope could be calculated. A nomograph prepared for this purpose is given in Figs. 6-1 and 6-2. Entering this diagram with the selected value of the Froude number and using the chosen discharge, one may read directly the slope and the corresponding revolution counter setting, the tail gate height and the normal depth.

For definition of the Geometries see Fig. 3-14.





TABLE - SELECTION OF VARIABLES FOR FREE

## SURFACE FLOW TESTS

Geometry Variable	Ia	Ib	II	III	IV	Va	Vb	VI	VII
F	.04-1.25	.04-.804	.05-0.4	0.1 0.15 0.25 0.3 0.4 0.5	0.1 0.15 0.2 0.25 0.3 0.4 0.5-0.25	0.1 0.14 0.2-0.3 0.4-0.5	0.09-0.5	0.1-0.475	0.1-0.5
M	.3-.9	0.3-0.9	0.3 0.5 0.7 0.9	0.3 0.5 0.7	0.3 0.5 0.7	0.3 0.5 0.7 0.9	0.2 0.5	0.3 0.5 0.7	0.35 0.5 0.75
$\frac{I}{b}$	0	0 0.5 1.0	0.25	0.25	0	0	0.5	0	0
$\frac{d}{b}$	0	0	0 0-7.5 7.5-15 15-25 25-30	0	0	0	0	0	0
$\phi_1$	90	90	90	30 45 60 90	90	90	90	90	90
$\phi_2$	0	0	0	0	0	0 15 30 45	15 30	0	0
$\beta$	0	0	0	0	0	0	0	0	0 0.3 0.5
N	1	1	1	1	1	1	1	1	1
n	.011 .0238	.0238	.0238	.0238	.0238	.0238	.0238	.0238	.0238
e	0	0	0	0	0.0 0.8 0.85 0.9 0.95 1.0	0	0	0	0



## VI-2 Obtention of Uniform Flow

Once the Froude number and the discharge have been selected and the normal depth slope and tail gate setting have been calculated, the discharge is adjusted to the proper value, the slope and the tail gate are set to the calculated values.

The depth of flow is then measured at several stations along the flume, usually at 10 foot intervals from station 10 to station 50. If the depth at these stations varies by more than 1 mm the tail gate position is adjusted until uniform flow is obtained.

Once the Froude number and the discharge have been calculated, the slope and tail gate setting have been calculated. The discharge is adjusted to proper value, the slope and the tail gate are set to the calculated values. The depth of flow is then measured at several stations along the channel. If 10 foot intervals from station 10 to station 20, if the depth is less than 10 feet, it is measured by more than 1 foot. The tail gate position is adjusted until the desired depth is obtained.

### VI-3 Free Surface Measurements

Usually the water surface measurements were taken along the centerline of the arch opening. Additional measurements of the free surface were taken for two-span arch bridge models, for two-dimensional segment models, for three-dimensional skewed models. The upstream face of the model was located at station 30. The maximum backwater depth occurred usually between stations 20 and 30. Water surface measurements were usually taken from station 15 to the end of the regain curve downstream of the bridge. The interval of the measurements varied with the slope and the curvature of the free surface, but in the vicinity of the point of maximum backwater depth, measurements were made at intervals of 0.5 to 1 foot.

The water surface measurements were taken by means of an electric point gage, which could be read to the nearest 0.1 mm.





#### VI-4 Data Processing

In the theoretical development it has been shown (see equ. 3-9-29 and 3-9-35) that the ratio of the backwater depth  $Y_1$  to the normal depth  $Y_n$  could be expressed as a function of the ratio of the Froude number  $F_n$  (which is the governing flow parameter) to the channel opening ratio  $M^0$  (which is the governing geometric parameter) of the types:

$$\frac{Y_1}{Y_n} = f_1 \left( \frac{F_n}{M^0} \right)^{2/3} \quad (6-4-1)$$

or

$$\frac{Y_1}{Y_n} = f_2 \left( \frac{F_n}{M^0} \right)^2 \quad (6-4-2)$$

It was found from the experimental data analysis that it was more convenient to present the backwater superlevation ratio  $h_1^*/Y_n$  as a function of  $F_n/M^0$  in the forms

$$\frac{Y_1}{Y_n} - 1 = \frac{h_1^*}{Y_n} = f_3 \left( \frac{F_n}{M^0} \right)^{2/3} \quad (6-4-3)$$

$$\frac{Y_1}{Y_n} - 1 = \frac{h_1^*}{Y_n} = f_4 \left( \frac{F_n}{M^0} \right)^2 \quad (6-4-4)$$

The general form of equ. 6-4-3 was used in the presentation of the results in the several progress reports. This presentation of the results is given in the following chapter.

In addition, a new analysis of the data was made according to the form of equ. 6-4-4. This presentation is given for the first time in this report. The value of obstruction head loss coefficients have been calculated for all seven geometries by means of the formula (see equ. 3-8-13).

$$K = \frac{h_1^*}{V_{n2}^2/2g} = \alpha \left[ \left( \frac{A_{n2}}{A_4} \right)^2 - \left( \frac{A_{n2}}{A_1} \right)^2 \right] \quad (6-4-5)$$

In the theoretical development of the model, it is assumed that the ratio of the reaction depth  $\delta$  to the total depth  $H$  is small, i.e.,  $\delta/H \ll 1$ . In this case, the function of the ratio of the reaction depth  $\delta$  to the total depth  $H$  is given by the following expression (see, for example, [1]):

$$\frac{\delta}{H} = \frac{1}{2} \left( \frac{1}{1 + \frac{1}{2} \frac{H}{\delta}} \right)^{1/2}$$

$$\frac{\delta}{H} = \frac{1}{2} \left( \frac{1}{1 + \frac{1}{2} \frac{H}{\delta}} \right)^{1/2}$$

It was found from the experimental data that the ratio of the reaction depth  $\delta$  to the total depth  $H$  is small, i.e.,  $\delta/H \ll 1$ . In this case, the function of the ratio of the reaction depth  $\delta$  to the total depth  $H$  is given by the following expression (see, for example, [1]):

$$\frac{\delta}{H} = \frac{1}{2} \left( \frac{1}{1 + \frac{1}{2} \frac{H}{\delta}} \right)^{1/2}$$

$$\frac{\delta}{H} = \frac{1}{2} \left( \frac{1}{1 + \frac{1}{2} \frac{H}{\delta}} \right)^{1/2}$$

The results of the experimental investigation show that the ratio of the reaction depth  $\delta$  to the total depth  $H$  is small, i.e.,  $\delta/H \ll 1$ . In this case, the function of the ratio of the reaction depth  $\delta$  to the total depth  $H$  is given by the following expression (see, for example, [1]):

In addition, it was found that the ratio of the reaction depth  $\delta$  to the total depth  $H$  is small, i.e.,  $\delta/H \ll 1$ . In this case, the function of the ratio of the reaction depth  $\delta$  to the total depth  $H$  is given by the following expression (see, for example, [1]):

$$\frac{\delta}{H} = \frac{1}{2} \left( \frac{1}{1 + \frac{1}{2} \frac{H}{\delta}} \right)^{1/2}$$

The value of  $\alpha$  used in the computations was 1.20, which was obtained from velocity distribution measurements. (See chapter VII).

It has been shown (see equ. 3-9-10) that the backwater ratio  $\frac{h_1^*}{Y_n}$  is proportional to the square of the ratio of Froude number  $F_n$  and the contraction ratios:

$$\frac{h_1^*}{Y_n} = D \left( \frac{F_n}{M^*} \right)^2$$

6)

The value of D was calculated from equ. 3-9-17, namely

$$D = n C \left[ \left( \frac{F_n}{M^*} \right)^2 \right]^{n-1}$$

(6-4-7)

and plotted vs.  $\frac{h_1^*}{Y_n} / \left( \frac{F_n}{M^*} \right)^2$  for the purpose of evaluating the consistency of the results.

A geographical multiple correlation technique was used for the presentation of the data of geometries II to VII. This technique is described in the following paragraphs. The remaining calculations were performed on the digital computer. Figure 6-3 shows the program flow chart for data analysis using Fortran II on the IBM 7090 computer.

value of  $c$  used in the computation was 1.70, which was obtained from  
 adaptation measurements. (See chapter VII).

It has been shown (see eqn. 3-9-10) that the best-fit ratio  $\frac{M}{H}$  is  
 the square of the ratio of the number of molecules  $N$  and the number of

$$\frac{M}{H} = \left( \frac{N}{H} \right)^2$$

a value of  $D$  was calculated from eqn. 3-9-11, namely

$$D = \frac{1}{2} c \left[ \left( \frac{M}{H} \right)^2 \right]^{1/2}$$

plotted vs.  $\left( \frac{M}{H} \right)^2$ . The program of calculation was written in  
 FORTRAN.

A geographical map of the area of study was obtained from the  
 data of location in the VII. The map was drawn on a grid of  
 squares. The remaining calculations were performed on the grid.  
 It shows the program line about the data in the map.



## VI-5 Four Variables Graphical Multiple Correlation

### (I) Principles of correlation

- A. The coaxial method of graphical correlation is based on the premise that if any important factor is omitted from a relation, the scatter of the points in a plotting of the observed values of the dependent variable vs. the values computed from the relation will be at least partly explained by the omitted factor. In other words, if the points on such a plotting are labeled with the corresponding values of the new factor, a family of curves can be drawn to modify the values computed from the original relation. For example:
- B. For 2-D segment arch bridge model test, the following relation resulted from dimension analysis for the unsubmerged case

$$\frac{Y_1}{Y_n} = f(F_n, M, \beta)$$

### (II) Procedures for Correlation

- (1) Tabulate the required data:  $F_n, \beta, M, Y_1/Y_n$  for each run
- (2) Consider  $\frac{Y_1}{Y_n}$  as the dependent variable, plotted along the final axis.  
(See fig. 6-4)

The  $F$  values vary in all tests and should be used as the first correlating variable. The values of  $\beta$  and  $M$  are fixed for a given model; it will be convenient to consider them in the second and third steps (quadrants A and B).

- (3) Assume  $\frac{Y_1}{Y_n} = f_1(F, \beta)$  and neglect the variable  $M$ .

### (III) Remark:

The reading sequence in Fig. 6-10 should follow the sequence of correlation. For example, given  $F_n, \beta, M$ , to find  $Y_1/Y_n$ . The sequence of reading must follow the sequence  $F_n \rightarrow \beta \rightarrow M \rightarrow Y_1/Y_n$ . The sequence  $F_n \rightarrow M \rightarrow \beta \rightarrow Y_1/Y_n$  does not yield the correct answer.

(I) Principles of correlation

A. The classical method of graphical correlation is based on the premise that if any important factor is omitted from a relation, the statistical points in a plotting of the observed values of the dependent variable against the values computed from the relation will be at least partly scattered by the omitted factor. In other words, if the points on such a plot are labeled with the corresponding values of the new factor, a smooth curve can be drawn to modify the values computed from the relation. For example:

B. For 3-4 segment least squares method, keep the following relation from dimension analysis for the unsmoothed curve:

$$\frac{Y}{Y_0} = f(X_1, X_2, X_3)$$

(II) Procedures for Correlation

(1) Calculate the required data:  $\bar{X}_i, \bar{Y}, S_{X_i}, S_{Y}, S_{X_i X_j}, S_{X_i Y}, S_{X_j Y}$  for each variable.

(2) Consider  $\frac{Y}{Y_0}$  as the dependent variable, plotting it against  $X_1, X_2, X_3$ . (See fig. 5-4)

The Y values vary in all four and should be used as the Y variable. The values of  $\bar{X}_i$  are the same for all four variables. The values of  $\bar{Y}$  are the same for all four variables. The values of  $S_{X_i X_j}$  and  $S_{X_i Y}$  are the same for all four variables. The values of  $S_{X_j Y}$  are the same for all four variables.

(3) Assume  $\frac{Y}{Y_0} = f(X_1, X_2, X_3)$  and use the method of least squares to find the values of  $f$ .

(III) Remarks:

The reading sequence in fig. 5-10 should follow the sequence of variables. For example, given  $\bar{X}_1, \bar{X}_2, \bar{X}_3$ , to find  $\bar{Y}$ . The sequence of reading should follow the sequence  $\bar{X}_1 \rightarrow \bar{X}_2 \rightarrow \bar{X}_3 \rightarrow \bar{Y}$ . The sequence  $\bar{X}_1 \rightarrow \bar{X}_2 \rightarrow \bar{X}_3 \rightarrow \bar{Y}$  does not yield the correct answer.

$F_n$  is used as the abscissa and  $\frac{Y_1}{Y_n}$  as the ordinate, as shown in Fig. 6-5.

A point  $P_1(F_n, Y_1/Y_n)$  can be located in the quadrant A and the  $\beta$  value of this point is shown by an assigned symbol. For example, in Fig. 6-5 symbol O shows that the value of  $\beta$  is 0.5.

In Fig. 6-5, the points are scattered because the essential factor M has not been considered. However, an average line for each  $\beta$  can be found through the average positions of the points.

(4) Add the factor M (see Fig. 6-6),  $\frac{Y_1}{Y_n} = f_2(F_n, \beta, M)$

With given values of  $F_n$ ,  $\beta$  and  $Y_1/Y_n$ , a point  $P_2$  may be located and the value of M is labeled or shown by an assigned symbol. An average line for M is plotted through the average position of the points.

(5) Check the accuracy of the above correlation. See Fig. 6-7.

With given values of  $F_n$ ,  $\beta$  and M, a computed  $Y_1/Y_n$  can be found from Fig. 6-6. Then the computed  $Y_1/Y_n$  and the measured  $Y_1/Y_n$  define a point in quadrant C of Fig. 6-7. Draw a line through the origin bisecting the quadrant C. Then the degree of scatter of the points around the line will show the degree of accuracy of the above correlation.

(6) The  $\beta$ -lines and the M-lines in quadrants A and B are adjusted to improve the correlation, see Fig. 6-8.

a. With the given values of  $F_n$ , M,  $Y_1/Y_n$  and using the M-lines obtained in the previous step, the points are adjusted in quadrant A. The scatter is reduced, and a better fit of the points is obtained.

b. In the same way with given values of  $F_n$ ,  $\beta$ ,  $Y_1/Y_n$  and the newly obtained  $\beta$ -lines, new M-lines are obtained and their accuracy is improved.

c. Then check the accuracy of the correlation in quadrant C. The points will be closer to the bisecting line than before. This means that the accuracy has been improved.

is used as the abscissa and  $\frac{\bar{Y}}{N}$  as the ordinate, as shown in Fig. 6-2. The point  $P_1(\bar{Y}_1, \frac{\bar{Y}_1}{N})$  can be located in the quadrant 4 and the  $\bar{Y}$  value of point 1 is shown by an assigned symbol. For example, in Fig. 6-2, the value of  $\bar{Y}$  is 0.5.

In Fig. 6-2, the points are scattered because the essential factor  $N$  has not been considered. However, an average line for each  $\bar{Y}$  can be found through the positions of the points.

(1) Add the factor  $N$  (see Fig. 6-2)  $\frac{\bar{Y}}{N} = \frac{1}{2} \cdot \frac{1}{N} = \frac{1}{2N}$  to the given values of  $\bar{Y}_1, \bar{Y}_2, \dots, \bar{Y}_N$  and  $\frac{\bar{Y}}{N}$  to get the new values  $\bar{Y}_1', \bar{Y}_2', \dots, \bar{Y}_N'$  and  $\frac{\bar{Y}'}{N}$ . The points are labeled or shown by an assigned symbol. An average line for each  $\bar{Y}$  is found through the average position of the points.

(2) Check the accuracy of the above correction. For this, the given values of  $\bar{Y}_1, \bar{Y}_2, \dots, \bar{Y}_N$  and  $\frac{\bar{Y}}{N}$  are corrected to  $\bar{Y}_1', \bar{Y}_2', \dots, \bar{Y}_N'$  and  $\frac{\bar{Y}'}{N}$  and the measured  $\bar{Y}_1', \bar{Y}_2', \dots, \bar{Y}_N'$  values are compared with the computed  $\bar{Y}_1', \bar{Y}_2', \dots, \bar{Y}_N'$  values. Then the average line through the origin is drawn. The points are scattered around the line (1) and the accuracy of the correction is checked.

(3) The  $\bar{Y}$ -lines and the  $N$ -lines in quadrant 4 and 5 are adjusted to the correlation, see Fig. 6-3.

a. With the given values of  $\bar{Y}_1, \bar{Y}_2, \dots, \bar{Y}_N$  and using the  $N$ -lines, the points are scattered around the origin. The average line through the origin is drawn.

b. In the same way with given values of  $\bar{Y}_1, \bar{Y}_2, \dots, \bar{Y}_N$  and the  $\bar{Y}$ -lines, new  $N$ -lines are obtained and their accuracy is improved.

c. Then check the accuracy of the correlation in quadrant 4. The points are scattered around the bisecting line than before. This means that the accuracy has been improved.



d. Try the procedures (a to c) a number of times until the points in quadrant no longer change their position, then the accuracy of the correlation has reached its maximum possible value.

e. The  $\beta$ -lines and M-lines may also be presented as shown in Fig. 6-9.

(7) Change Fig. 6-9 to a more convenient form, Fig. 6-10, by combining quadrants and B together.



8. Try the procedure (a) in (b) of item 7. If the system is not  
no longer change their position, then the system of the computer and  
maximum possible value.

9. The 8-11th and 11-12th are given as shown in Fig. 1-12.  
(7) Change Fig. 8-9 to a new format. Fig. 8-10, by reading the  
and H together.

## VII ANALYSIS OF TEST RESULTS

7-1 Geometry I

## a) Introduction

The results discussed in this chapter pertain to the large flume model tests. For the two dimensional model tests in smooth and rough boundaries, the backwater ratio and the discharge coefficient are given in terms of the channel opening ratio and the normal depth Froude Number. For model tests in rough boundaries, the locations of the points of maximum and minimum depths are given. A method for estimating the minimum depth is presented. The effects of different channel roughnesses and different bridge lengths on the backwater ratio and on the discharge coefficient are compared. Finally, surface topography and velocity profiles at typical sections are obtained and the kinetic energy and momentum correction factor are calculated. It should be restated that all the curves and conclusions presented are limited to symmetric single span arches without entrance chamfering or rounding and skew. (See figures 3-14).

## b) Smooth Boundaries - Tests by H. J. Owen

The test data and the calculated values of the discharge coefficient  $C_d$  of the contraction coefficient  $f_c$ , and of the Reynolds number are presented in table 7-1-1. The ratio of the backwater depth to the normal depth  $T_1/T_0$  is plotted versus the ratio of the velocity head to normal depth with the contraction ratio  $M$  as a parameter in figure 7-1-1. The ratio of the velocity head to the normal depth is a measure of the kineticity of the flow, it is exactly half of the kineticity as defined by Bakhtmeteff, that is, half the square of the Froude number. The discharge coefficient  $C_d$  calculated from equation 3-7-2 is plotted versus the ratio of the velocity head to the normal depth with the channel width ratio  $M$  as a parameter in figure 7-1-2. The consistency of the data is well illustrated by the lack of scatter of the



experimental points as plotted in figures 7-1-1 and 7-1-2. These test results may be compared with the small scale tests done as part of the Preliminary Tests (see Chapter IV) for the contraction ratio of 0.5 which is common to both test series. Inspection of figure 4-8 and figure 7-1-1 and 7-1-2 shows that the values are almost identical. For example, at a Froude number of 0.2, the value of the discharge coefficient  $C_d$  from the small scale tests (figure 4-8) is 0.38 and the super-elevation ratio  $Y_1/Y_n$  is 1.1. Compared to this, the large scale tests, (Figures 7-1-1 and 7-1-2) give  $C_d$  as 0.275 and  $Y_1/Y_n$  as 1.119 for a kineticity of 0.02 which corresponds to the Froude number of 0.2. At a Froude number of 0.4 the results of the small scale tests indicated  $C_d$  was equal to 0.53 and  $Y_1/Y_n$  was 1.4. Similarly, at corresponding kineticity of 0.08, the large scale tests showed  $C_d$  to be 0.483 and  $Y_1/Y_n$  to be 1.432. The reliability of the data may be better discussed in terms of the values of the friction coefficient and of the backwater ratio.

The Darcy-Weisbach friction factor and the Reynolds number for the uniform flow established before each test were calculated in table 7-1-1 as follows:

$$R = \frac{VR}{\nu}$$

$$f = \frac{8gRS}{V^2}$$

The experimental friction factors were compared to the theoretical values obtained by adapting the Blasius and Prandtl formulas for flow in smooth pipes to the rectangular open channel.

The formulas for smooth pipe flow are:

$$\text{Blasius } f = 0.3164 \left( \frac{VD}{\nu} \right)^{-1/4} \quad Re < 10^5$$

$$\text{Prandtl-Von Karman } \frac{1}{\sqrt{f}} = 2.0 \log \left( \frac{VD}{\nu} \sqrt{f} \right) = 0.8$$

Replacing  $D$  by  $4R$  and simplifying, the equations become:

Experimental points are plotted in Figure 1 and are labeled. The solid line represents the theoretical curve for the case of a constant temperature. The dashed line represents the case of a variable temperature. The dotted line represents the case of a constant temperature with a correction for the effect of the temperature on the rate of reaction. The solid line is the best fit to the experimental points. The dashed line is the best fit to the experimental points with a correction for the effect of the temperature on the rate of reaction. The dotted line is the best fit to the experimental points with a correction for the effect of the temperature on the rate of reaction and a correction for the effect of the temperature on the rate of reaction.

$$k = \frac{A}{T^n} e^{-\frac{E}{RT}}$$

The experimental points are plotted in Figure 1 and are labeled. The solid line represents the theoretical curve for the case of a constant temperature. The dashed line represents the case of a variable temperature. The dotted line represents the case of a constant temperature with a correction for the effect of the temperature on the rate of reaction. The solid line is the best fit to the experimental points. The dashed line is the best fit to the experimental points with a correction for the effect of the temperature on the rate of reaction. The dotted line is the best fit to the experimental points with a correction for the effect of the temperature on the rate of reaction and a correction for the effect of the temperature on the rate of reaction.

$$k = \frac{A}{T^n} e^{-\frac{E}{RT}}$$

Using the values of  $k$  and  $E$  calculated from the experimental points



$$\text{Blasius } f = 0.223 \left( \frac{VR}{\nu} \right)^{\frac{1}{4}}$$

$$\text{Prandtl-Von Karman } \frac{1}{\sqrt{f}} = 2.0 \log \left( \frac{VR}{\nu} \sqrt{f} \right) + 0.40$$

Powell and Posey<sup>2</sup>, working with a triangular flume found the formula governing their friction factor to be

$$\frac{1}{\sqrt{f}} = 2.074 \log (Re \sqrt{f}) - 0.797$$

for tranquil flow in a smooth channel. The comparison between experimental values and the theoretical formulas is shown in figures 7-1-3 and 7-1-4. In figure 7-1-3 the experimental values of the Darcy-Weisbach coefficient  $f$  are plotted versus the Reynolds number. Both  $f$  and  $R$  are as defined above based on the hydraulic radius. Also plotted on the same figure are the Blasius and Von-Karman relationship as well as the general range of experimental values obtained by Lansford and Robertson<sup>3</sup> for smooth triangular channels.

In figure 7-1-4 the friction coefficient  $f$  and the Reynolds number are based on the normal depth, assuming two dimensional flow. Although this assumption is not completely true for the depth to width ratio used in the experiments this was done to compare the data with the experiments of Owen<sup>4</sup> which were done in a glass channel.

In general, as shown in figure 7-1-4 the data fall above the theoretical lines which are a lower limit for a perfectly smooth boundary. The average friction coefficient is  $f = 0.021$  which corresponds to an absolute roughness of approximately  $\epsilon = f(f) = 0.0025$  feet. This corresponds to the irregularities of the epoxy resin of the channel finish.

The backwater ratio  $h_1^*/\Delta h$  for each model test was compared to the values obtained by Tracy and Carter<sup>5</sup> for rectangular constrictions. This comparison is shown in figure 7-1-5 which shows that the backwater ratios are of the same order of magnitude although different as may be expected with different boundary geometries.



### c) Smooth Boundaries - Tests by P. F. Biery

The experimental results of the two-dimensional semi-circular arch model tests in the large flume with smooth boundaries were plotted as the backwater ratio  $Y_1/Y_n$  vs. the channel opening ratio  $M^0$  with the normal depth Froude number  $F_n$  as the parameter. This plot is shown in Fig. 7-1-6. As would be expected, the ratio  $Y_1/Y_n$  would decrease to unity for all Froude numbers as the value of  $M^0$  approaches 1.00. Also, it goes to infinity as  $M^0$  goes to zero. In a similar manner, the discharge coefficient  $C_d$  was plotted vs.  $M^0$  for  $F_n$  and is shown in figure 7-1-7. The value of  $C_d$  tends to 0.611 at  $M^0 = 0$  and approaches the same value as the parameter  $F_n$  when  $M^0 = 1$ .

The curves of figure 7-1-6 and 7-1-7 have actually been interpolated for constant Froude numbers. Although the results covered the entire range of variables, the Froude number of normal depth was never exactly equal to 0.5, 0.6 or any other value of the parameter on the figure. The amount of error produced during the interpolating process was found in most cases to be less than one percent. The raw data and calculations are given in tables 7-1-2 and 7-1-3 respectively.

The data of P. F. Biery for smooth boundaries have been processed and analyzed as described in section VI-4. The backwater superelevation ratio  $h_1^*/Y_n$  is plotted as a function of  $(F_n/M^0)^2$  in Fig. 7-1-8; the head loss coefficient  $K$  is given in terms of  $M^0$  in Fig. 7-1-9, and the backwater ratio coefficient  $D$  is given in Fig. 7-1-10.





## VII-2 Geometries Ia and Ib - Rough Boundaries - Tests by P. F. Biery (See Fig. 3-14 for definitions of geometries Ia and Ib).

### a) Selection of Rough Boundary Model Tests

From the nomographic chart, (Fig. 6-2) the conditions for the rough boundary model tests were selected. The X's in the table below indicate the selected normal depth conditions for each of which the following values of  $M$  and  $L/b$  were tested.

For  $M = b/B = 0.3, 0.5, 0.7, 0.9$

and  $L/b = 0.0, 0.5, 1.0$

Flow Rate	Froude Number										
	0.05	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70 0.80 0.90
1 cfs	X		X			X			X		X
2 cfs		X		X			X			X	X
3 cfs			X		X			X			X

### b) Test Data

Table 7-2-1 presents the raw measurements of all of the large flume, rough boundary, semicircular tests. Included are both the two and three dimensional results. The designation of the run numbers is as follows. The first number represents the normal depth set-up. The second number represents the particular model being tested. The pertinent data and calculations are summarized in Table 7-2-2.

The particular measurements that were taken on each of the smooth and rough tests in the large flume were those required to calculate the following quantities: the hydraulic radius, the Reynolds number, the Froude number, the Darcy-Weisbach friction factor, the channel opening ratio  $M'$ , the discharge coefficient, the backwater ratio ( $Y_1/Y_n$ ), the backwater superelevation ( $h_1^*$ ), the surface profile ratio ( $h_1^*/\Delta h$ ), the length to the maximum backwater ( $L_{1-2}$ ), the length to the point of minimum depth ( $L_{2-3}$ ), the length  $L_{1-3}$ , and the Manning's  $n$ . (See figure 3-1 for the definition of terms.)





In view of the large amount of data that was to be analyzed and the repetitive character of the calculations, a program was prepared for processing the data on the Royal McBee LGP-30 digital computer.

In Table 7-2-3, the surface topography measurements for run number 4-4 are listed. It was felt that this run was indicative of average natural stream conditions. For the same run, the velocity measurements at the uniform depth, maximum depth, vena contracta and minimum depth are given in Table 7-2-4. In addition to the uniform depth isovel diagram of run number 4-4 above, velocity measurements of uniform flow were also taken for normal depth runs number 2 and 10. This data is also listed in Table 7-2-4.

With the isovel diagrams for uniform flow, the kinetic energy correction factor  $\alpha$  and the momentum correction factor  $\beta$  were determined. This was accomplished by obtaining the areas between two adjacent constant velocity lines with an area planimeter. Once the areas were determined, the equations for  $\alpha$  and  $\beta$  were solved in the following form.

$$\alpha = \frac{\int v^3 ds}{V^3 A} = \frac{\sum_{i=1}^n v_i^3 \Delta a_i}{V^3 A} \quad (7-2-1)$$

and

$$\beta = \frac{\int v^2 ds}{V^2 A} = \frac{\sum_{i=1}^n v_i^2 \Delta a_i}{V^2 A} \quad (7-2-2)$$

where  $n$  = number of sub-areas

$$V = \frac{\sum_{i=1}^n v_i \Delta a_i}{A} \quad (7-2-3)$$

$$A = \sum_{i=1}^n \Delta a_i \quad (7-2-4)$$

### e) Test Results

#### a) Backwater ratio and discharge coefficient

The backwater ratio is plotted vs. the channel opening ratio with the normal depth Froude number as a parameter for the two-dimensional semicircular arch models as observed in the large flume with rough boundaries. In view of the importance of these curves, the scale was expanded and the results are shown in two parts. Figure



7-2-1a gives the results of  $Y_1/Y_n$  vs.  $M^0$  for the range of backwater ratios less than 1.50. For the ratios greater than 1.50, figure 7-2-1b should be used.

As for the smooth boundaries, the experimental values of the discharge coefficient for the same test conditions are presented in figure 7-2-2. This figure and figures 7-2-1a and b have been interpolated for constant Froude numbers. The hump that appears in the Froude number lines of 0.25 to 0.60 was a phenomena which appeared in all of the curves of  $C_d$ . This was true for the smooth, rough and all  $L/b$  plots.

When compared to the preliminary test results of Fig. 4-8, the values of the backwater ratio for a given  $F_n$  and  $M^0$  are almost identical.

### β) Location of the points of maximum backwater, and minimum depth

In order to describe the centerline profile, it is desirable to have an estimate of the distance from the upstream face of the constriction to the point of maximum backwater elevation. This distance is referred to as  $L_{1-2}$ . Because of the flatness of the surface profile in the vicinity of the maximum point, it was extremely difficult to get an exact measurement of  $L_{1-2}$ . The actual measurements taken could have been in error by as much as  $\pm 0.5$  feet. However, with the large amount of data which was available, it was possible to study  $L_{1-2}$  on an average basis. Average values of  $L_{1-2}$  were calculated for several combinations of  $b/B$ ,  $L/b$ ,  $L/B$ , etc. In this manner, it appeared that the effect of the variable bridge length and the change in  $F_n$  were of the same order of magnitude as the experimental error. The most consistent relationship was found by plotting the dimensionless ratio  $L_{1-2}$  vs. the Froude number  $F_n$  with  $M = b/B$  as the parameter. This relationship is shown in figure 7-2-3a. The values of  $L_{1-2}$  obtained from the smooth boundary tests also compared favorably with figure 7-2-3a. In a similar manner it was found that the length  $L_{1-3}$  (distance from the maximum depth point to the minimum depth point) varied only with the constriction geometry. The values of  $L_{1-3}/b$  are plotted vs.  $M = b/B$  with  $L/b$  as a parameter in figure 7-2-3b. These curves are good for both two and three dimensional semicircular arch bridges.







### f) Determination of the minimum depth

Several other investigators have used the Froude number at section 3 ( $F_3 = V_3/\sqrt{gy_3}$  see figure 3-1) as an estimator of the maximum backwater. Others have used  $F_3$  as a controlling parameter in making indirect measurements of flood discharges. Due to the extremely irregular flow pattern at the minimum point, it would seem that the use of  $F_3$  may be misleading. In the present research, the normal depth Froude number  $F_n$  was found to be a very reliable estimator of  $Y_1/Y_n$ . In order to test the variability of  $F_3$  with  $F_n$ , a correlation curve of  $F_3/F_n$  vs.  $F_n$  was prepared. This curve is shown in figure 7-2-4. Below a Froude number of 0.5, the correlation was good. However, above  $F_n = 0.5$ , the depth  $y_3$  was often below the critical depth and the correlation of  $F_3/F_n$  to  $F_n$  was very poor. The scatter seemed to increase with increasing values of  $L/b$ . Therefore, only the test results of the  $L/b = 0$  tests are shown. If used with caution, these curves can be used to estimate the minimum depth  $y_3$ . It appears from this curve that  $F_n$  is a much more reliable estimator than  $F_3$ .

### g) Regain Curve Length

The regain curve was measured for a few runs. This was done in order to establish the fact that the water surface profile returns to normal depth before the end of the testing flume was reached. The tests selected were those which would have the longest regain curve. The results are summarized below.

Run No.	M	L/b	$F_n$	$L_{2-4}$
1-4	0.491	0.0	0.0489	20 ft.
2-7	0.693	0.0	0.1005	9 ft.
4-4	0.491	0.0	0.1984	15 ft.

In all cases the regain curve was within the test section.

### h) Comparisons of roughness effects

Comparisons between the model tests in the smooth and rough channel were made by plotting the backwater ratio and the discharge coefficient against the normal depth Froude number  $F_n$  for constant channel opening ratios. Similar comparisons



were made between the several three-dimensional model tests in the rough flume.

The values of the backwater ratio  $Y_1/Y_n$  and the discharge coefficient  $C_d$  in the smooth and rough channel boundaries are compared in figures 7-2-5a and 7-2-5b. It appears that the values are essentially the same for both smooth and rough conditions at Froude numbers  $F_n$  less than 0.5. Since the practical range of Froude numbers for natural channels are those less than 0.5, these curves show that for all practical purposes the effect of roughness can be ignored.

### 5) Comparison of bridge length effects

Similarly, all of the  $L/b$  results were compared at constant values of the channel opening ratio  $M^0$ . Figures 7-2-6a and b illustrate these comparisons. Again it appears from the plots that for the practical range of field conditions ( $L/b \leq 1.0$  and  $F_n \leq 0.5$ ) the effect of bridge length is negligible. The effect of length did seem to increase with a decrease in the channel opening ratio. However, as the value of  $M^0$  gets small, the physical proportions are closer to those of a culvert rather than a bridge opening.

### 7) Surface topography

In order to complete the analysis of the maximum backwater, additional studies were made of the velocity distributions and the surface profiles. These studies were made for the condition of a sharp-crested semicircular constriction with  $M = b/B = 0.5$  and  $F_n$  approximately 0.20.

A detail of the surface topography both upstream and downstream of the model was observed. The results of this study are shown in figure 7-2-7. The numbers shown indicate the depths in centimeters. Only a detail of one half of the surface is given since the pattern is essentially symmetrical. The graph shows lines of equal surface elevation. The centerline profile is also given in the figure. It is interesting to note that the actual maximum water surface elevation is not along the centerline, but on the upstream face of the abutment. Although this may be expected, since there is a stagnation point at the abutment, the actual magnitude of the difference in elevation between the centerline maximum elevation and the





actual maximum is the important question. The actual maximum shoreline elevation was found to exceed the maximum centerline elevation by as much as 5% of the centerline depth. This fact was verified in the surface topographies taken at other conditions. Liu<sup>6</sup>, as well as Herbich<sup>9</sup> gave similar surface topographies of other geometric constrictions, and the differences in water surface elevations was again found to be about 5% of the centerline depth.

### 1) Velocity profiles

Traverses were run with the Prandtl Tube at four sections with the  $M = 0.5$ ,  $L/b = 0.0$  and  $F_n$  approximately 0.20 model tests. The first section was in the normal depth flow without the model. The second was at the section of maximum backwater, the third at the upstream face of the bridge and the fourth at the section of minimum depth. At the section of normal depth and maximum depth, vertical velocity traverses were taken at the centerline and 1 ft. and 2 ft. left and right. At the vena contracta, they were taken at the centerline, 0.5 ft. and 1 ft. left and right. Finally at the section of minimum depth, traverses were taken at the centerline, 1 ft., 1.5 ft., and 2.2 ft. left and right. In general a more detailed traverse was taken at the centerline of each section. From these measurements, plots of equal velocity lines were prepared for each section. This was done first by plotting the velocity profiles at each location within each section on arithmetic graph paper. Typical are the profiles shown in figure 7-2-8 at the maximum depth condition. From these curves, points of equal velocity were found and plotted in the appropriate location on a cross-section view of the channel. A composite picture of the isovel diagrams is shown in figure 7-2-9. Only half of the diagram is given due to symmetry. All of the diagrams were integrated with an area planimeter and the discharge so obtained was checked against the venturi meter discharge. In all cases they checked within 1%.

In addition to the isovel diagrams for uniform flow in figure 7-2-9, two other uniform flow velocity profiles were plotted. The test conditions were similar to those of a natural stream. All of the diagrams were integrated and the values of the





discharge, the kinetic energy correction factor and the momentum correction factor were computed. Listed below are the determined values of  $\alpha$  and  $\beta$  for each profile.

Q	Slope	$y_n$	Approx. $F_n$	$\alpha$	$\beta$
2 cfs	0.000131	0.799 ft.	0.10	1.145	1.055
1 cfs	0.000584	0.319 ft.	0.20	1.216	1.084
1 cfs	0.004080	0.173	0.50	1.250	1.090

k) The generalized backwater equation and head loss coefficients

With the introduction of the channel opening ratio  $M^0$ , the assumption was made that if properly interpreted, the backwater produced by constrictions of the same  $M^0$  would be equal, regardless of its geometry (i.e., a semi-circle, or a circular segment, or a rectangle etc.) as long as the constriction effects are not modified by skew, chamfers, eccentricity, wingwalls, etc.

To test this hypothesis, the results of this section (VII-2) are compared with the circular segment data obtained in the preliminary investigation (Fig. 4-8) and with the vertical board data given by Liu<sup>7</sup>. The latter tests were run in a flume which was wider than the large flume used in this investigation. The roughness pattern used by Liu was also different. It produced a Manning's  $n$  of 0.024. It is felt extremely interesting to note that the test data taken by three investigators in three different flumes and under three completely different constriction geometries produced almost identical results. This clearly verifies that, as defined, the channel opening ratio  $M^0$  is the governing geometric parameter. Of course, the data compared were those where the eccentricity was zero, the skew was zero, and the entrance was sharp. It is still necessary to apply correction terms for these conditions.

As mentioned previously in the analysis, a similarity was noticed between the several different backwater equations. The term  $(F_n/M^0)^{2/3}$  appeared in several solutions of  $y_1/y_n$ . In general it appeared that

$$y_1/y_n = C \left[ (F_n/M^0)^{2/3} \right]^\gamma \quad (7-2-5)$$



where  $C$  is a coefficient which would take into account the effects of the discharge coefficient, approach velocity, and non-uniform velocity distributions and other empirically determined factors. Equation 7-2-5 is actually the equation of a straight line on logarithmic paper with a slope of  $\gamma$ . A total of 50 semicircular  $L/b = 0$  test values, 44 vertical board values (Colorado) and 50 segment values were plotted in the form of  $Y_1/Y_n - 1$  vs  $(F_n/M^0)^{2/3}$  and are shown in figure 7-2-10. The value of  $Y_1/Y_n - 1$  was used instead of the backwater ratio. It is quite apparent that the data tends to collapse into one straight line relationship.

The method of least squares was applied to a random sample of the 144 test points to determine the empirical straight line relationship. After solving for  $\gamma$  and  $C$ , equation 7-2-5 became

$$Y_1/Y_n = 1 + 0.47 \left[ (F/M^0)^{2/3} \right]^{3.39} \quad (7-2-6)$$

Equation 7-2-6 is a very simple and easy solution for the backwater produced by any type of constriction. In actual practice, this equation will give as good an estimate of the maximum backwater  $y_1$  as any previously suggested method.

It has been suggested by G. F. Izzard that equation 7-2-6 could be approximated

$$Y_1/Y_n = 1 + 0.45 (F/M^0)^2 \quad (7-2-7)$$

and still fit the data very closely.

The data were also reanalyzed in terms of the simpler equation

$$\frac{h_1}{Y_n} = \frac{Y_1}{Y_n} - 1 = f \left( \frac{F}{M^0} \right)^2$$

Figures 7-2-11 to 7-2-13 give plots of this relation for values of  $L/b = 0; 0.5;$  and  $1.0$ . Fig. 7-2-14 summarizes the backwater ratio information for geometry I, for smooth and rough boundaries. The curves shown in this figure are the same as those previously obtained in figures 7-1-8 and 7-2-11 to 7-2-13. In addition, a least square fitting of all the data (smooth and rough) taken by P. F. Biery is given.







The head loss coefficient  $K$  is given as a function of  $M'$  for  $L/b = 0; 0.5; 1.0$  in figures 7-2-15 to 7-2-18. A summary of the head loss coefficient curves is given in fig. 7-2-18. The backwater ratio coefficient  $D$  is given in Fig. 7-2-19 to 7-2-21 corresponding to values of  $L/b = 0; 0.5$  and  $1.0$ .



### VII-3 Geometry II Tests by S. Lippai and T. P. Chang

#### Dual Parallel Three Dimensional Semi-Circular Arch Bridge Constrictions: (See Fig. 3-14 for definition of Geometry II)

For simplicity, only the case of two identical arch bridges placed parallel to each other and normal to the direction of flow, was considered. The effect of Froude Number ( $F_n$ ), the channel opening ratio ( $M^0$ ), and the distance between the centerlines of dual parallel bridges ( $l_d$ ), on the backwater ratio ( $Y_1/Y_n$ ) has been determined.

The raw and calculated data for the 117 tests are given in table 7-3. Typical surface profiles are shown in Fig. 7-3-0. Figures 7-3-1 to 7-3-5 were obtained by plotting backwater ratio  $Y_1/Y_n$  against the dimensionless bridge spacing  $bl_d/A_{n2}$  with the channel opening ratio  $M^0$  as parameter for  $F_n = 0.10, 0.15, 0.20, 0.25, 0.30$  and  $0.40$ .

It was found that for low Froude Numbers ( $F_n \leq 0.25$ ) the backwater due to closely placed dual parallel bridges ( $bl_d/A_{n2} \leq 5$ ) was less than what it would have been for a single bridge. The lower part of the graphical correlation of Fig. 7-3-6 shows clearly this effect.

It was also found that for higher Froude Numbers ( $F_n \geq 0.25$ ) and small channel opening ratios ( $M^0 = 0.3$ ), the placing of models at  $bl_d/A_{n2} \cong 8$  to 9 resulted in strong wave action between the models and an abrupt increase in backwater ratio was observed as can be seen in Figures 7-3-3 to 7-3-5. For the latter conditions, the jet expansion below the upper bridge was unstable. It oscillated from the left to right and back with a period of about 2 sec. The backwater upstream of the upper bridge was minimum when the jet was symmetrical along the centerline. The backwater increased as the jet was deflected sideways. The values plotted were the maximum backwater elevations observed.

Figure 7-3-6 shows the graphical multiple correlation for 4 variables ( $F_n, M^0, Y_1/Y_n, bl_d/A_{n2}$ ). Knowing any three of them, the fourth one may be determined from Fig. 7-3-6.





A straight line relationship between  $Y_1/Y_n$  and  $(F_n/M^0)^{2/3}$  on log-log paper was obtained for dual parallel bridges placed at  $bL_d/A_{n2} = 0, 10, 20$ , and  $30$ . Figure 7-3-7 was arrived at through the following steps:

1. Fig. 7-3-6 was used to obtain values of  $Y_1/Y_n$  for  $bL_d/A_{n2} = 0, 10, 20, 30$   $M^0 = 0.3, 0.5, 0.7$  and  $0.9$ ,  $F_n = 0.10, 0.20, 0.30$  and  $0.40$ .
2. This data was processed and an arithmetic plot of  $Y_1/Y_n$  vs.  $(F_n/M^0)^{2/3}$  for  $bL_d/A_{n2} = 0, 10, 20$  and  $30$  was constructed.
3. To obtain a straight line relationship between  $Y_1/Y_n$  vs.  $(F_n/M^0)^{2/3}$  for  $bL_d/A_{n2} = 0, 10, 20$  and  $30$  on log-log paper, appropriate values of  $c$  were determined by using the method described in reference 8.
4. The curve of figure 8 doesn't apply to the unstable flow condition with heavy wave action between the dual bridges.

In addition the data were reanalyzed making use of the computer program.

The backwater superelevation ratio  $h_1^*/Y_n$  is plotted as a function of  $(F_n/M^0)^2$  in figures 7-3-8 to 7-3-13, for the following values of the parameter  $L_{db}/A_{n2}$ :

Fig. 7-3-8	$L_{db}/A_{n2} = 0$
Fig. 7-3-9	0 to 7.5
Fig. 7-3-10	7.5 to 15
Fig. 7-3-11	15 to 25
Fig. 7-3-12	25 to 30

The equation of a least square fitting is given for each range of the parameter  $L_{db}/A_{n2}$ . A summary of these curves is given in Fig. 7-3-13.

The head loss coefficient  $K$  is given in the channel opening ratio  $V'$  for the following values of the parameter  $L_{db}/A_{n2}$ :

Fig. 7-3-14	$L_{db}/A_{n2} = 0$
Fig. 7-3-15	0 to 7.5
Fig. 7-3-16	7.5 to 15
Fig. 7-3-17	15 to 25
Fig. 7-3-18	25 to 30

Whenever a good least square curve fitting could be obtained its equation is given on the graph. In the other cases, the average values of the several groups of test for a given value of  $M^0$  was obtained, and a line was fitted by eye through these points. Figure 7-3-19 is a summary of the head loss coefficient curves. Figure





7-3-20 gives the values of the backwater ratio coefficients  $D$ . The raw and calculated data for Geometry II are given in Table 7-3.



# III-4 Geometry III Texts by T. P. Chang

## Three Dimensional Semi-Circular Arch Bridge Constriction with Wingwalls (See Fig. 3-14 for definition of Geometry III)

The influence of wingwalls on the backwater ratio ( $Y_1/Y_n$ ) has been tested for wingwall angles  $\phi_1 = 30^\circ, 45^\circ, 60^\circ$  and  $90^\circ$ , using a model with  $L/b$  ratio of 0.25.

The raw and calculated data are listed in table 7-4. Figures 7-4-1 to 7-4-4 were obtained by plotting the backwater ratio, ( $Y_1/Y_n$ ) against the channel opening ratio, ( $M^1$ ) with the Froude Number ( $F_n$ ) as parameter for wingwall angles  $\phi_1 = 30^\circ, 45^\circ, 60^\circ$  and  $90^\circ$ .

Fig. 7-4-5 is obtained by graphical multiple correlation. Knowing any three of our variables,  $Y_1/Y_n$ ,  $F_n$ ,  $M^1$ , and  $\phi_1$ , the fourth one may be determined by this chart.

Fig. 7-4-6 shows the relation between the backwater ratio ( $Y_1/Y_n$ ) and ( $F_n/M^1$ )<sup>2/3</sup> with  $\phi_1$  as parameter. It was based on the graphical correlation of Fig. 7-4-5. Due to the indirect plotting method, the accuracy of Figure 7-4-6 is less than that of figures 7-4-1 to 7-4-4.

The data were reanalyzed making use of the computer program. The results are presented in the form of plots of the backwater superelevation ratio  $h_1^*/Y_n$  vs. the square of the ratio of the Froude number to the channel opening ratio ( $F_n/M^1$ )<sup>2</sup> for wingwall angle of  $30^\circ, 45^\circ, 60^\circ$  and  $90^\circ$  in figures 7-4-7 to 7-4-10.

For each value of the parameter  $\phi_1$ , the equation of the least square curve fitting is given on the figure. A summary of these results is given in Fig. 7-4-11.

The head loss coefficient  $K$  has been calculated for each of the wingwall angles. The results are presented in the form of plots of  $K$  vs. the channel opening ratio. Wherever possible a least square fitting of the data was obtained, and the equation of the line is given. In the other cases, average values of the coefficient  $K$  for grouping of points with the same value of  $M^1$  was obtained, and a straight line was fitted by eye through these average points. These results are presented in Fig. 7-4-12 to 7-4-15 for wingwall angles of  $30^\circ, 45^\circ, 60^\circ$  and  $90^\circ$ . A summary of the curves is presented in Fig. 7-4-16.





Finally, the values of the backwater ratio coefficient  $D$  are presented in fig. 7-4-17 to 7-4-20 for the four wingwall angles.

The raw and calculated data for Geometry III are given in Table 7-4.



VII-5 Geometry IV Two-Dimensional Semi-Circular Arch Bridge Constrictions with Eccentricity - Tests by T. P. Chang

(The eccentricity is defined as one minus the ratio of the small embankment to the larger embankment. (See Fig. 3-14 for definition of Geometry IV))

The influence of eccentricity on the backwater ratio along the centerline ( $Y_1/Y_N$ ) has been determined for eccentricities  $e = 0; 0.80; 0.85; 0.90; 0.95; \text{ and } 1.00$ . Figures 7-5-1 to 7-5-6 give the backwater ratio ( $Y_1/Y_N$ ) plotted vs. the channel opening ratio ( $M^0$ ) with the Froude Number as a parameter for each of the six eccentricities tested. Figure 7-5-7 shows the relation between the backwater ratio ( $Y_1/Y_N$ ) and  $(F_N/M^0)^{2/3}$  with the eccentricity as a parameter. Figure 7-5-7 was obtained by graphical multiple correlation.

The results of the re-analysis of the same data making use of the computer program is given in the following figures. The backwater superelevation ratio ( $h_1^*/Y_N$ ) is plotted vs.  $(F_N/M^0)^2$  for the six eccentricities tested in figures 7-5-8 to 7-5-13. For each eccentricity the equation of the least square curve fitting the data is given. A summary of the results is given in Fig. 7-5-14.

The values of the head loss coefficient  $K$  are plotted against the channel opening ratio  $M^0$  for each of the six eccentricities tested in figures 7-5-15 to 7-5-20. The straight lines were obtained by obtaining average values for  $K$  for groups of points having the same value of  $M^0$ . A straight line was fitted by eye through these average points. A summary of the head loss coefficient  $K$  is given in Fig. 7-5-21.

The values of the backwater ratio coefficient are given in Fig. 7-5-22 to 7-5-27.

The raw and calculated data for Geometry IV are given in Table 7-5.



## VII-6 Geometry Va

Two Dimensional Semi-Circular Arch Bridge Constrictions with Skew Tests by T.P. Chang  
(See Fig. 3-14 for definition of Geometry Va)

The influence of skew on the backwater ratio along the centerline,  $(Y_1/Y_N)$  has been determined for skew angles of  $\theta_2 = 0^\circ, 15^\circ, 30^\circ$  and  $45^\circ$ . The raw and calculated data are given in Table 7-6.

Fig. 7-6-1 to 7-6-4 were obtained by plotting the backwater ratios  $(Y_1/Y_N)$  against the channel opening ratio,  $(M^2)$  with Froude No.  $(F_N)$  as parameter for skew angles  $\theta_2 = 0^\circ, 15^\circ, 30^\circ$  and  $45^\circ$ .

Fig. 7-6-5 was obtained through graphical multiple correlation. Knowing any three of four variables,  $Y_1/Y_N$ ,  $F_N$ ,  $M^2$ , and  $\phi_2$ , the fourth variable may be determined from the correlation chart.

Fig. 7-6-6 shows a relation between  $Y_1/Y_N$  and  $(F_N/M^2)^{2/3}$  with  $\phi_2$  as parameter. This was based on the graphical correlation of Figure 7-6-5. Due to the indirect plotting method the accuracy of Fig. 7-6-6 is less than that of Figures 7-6-1 to 7-6-4.

The same data were reanalyzed making use of the computer program. The backwater ratio  $(h_1^*/Y_N)$  is plotted vs.  $(F_N/M^2)^2$  for the four skew angles tested in figures 7-6-7 to 7-6-10. The equation of the least square fit is given on each figure. A summary of these results is given on fig. 7-6-11. The values of the head loss coefficient  $K$  were plotted against the channel opening ratio  $M^2$  for each of the four skew angles tested in figures 7-6-12 to 7-6-15. The best fit lines were obtained by the least square method, and the equations of these lines are given in the respective figures. A summary of the head loss coefficients is given in figure 7-6-16. Finally the values of the backwater ratio coefficient  $D$  are given in figures 7-6-17 to 7-6-20. The raw and calculated data for Geometry Va are given in Table 7-6.





# VII-7 Geometry Vb

## ree-Dimensional Semi-Circular Arch Bridges Constrictions with Skew Tests by T.P. Chang (See Fig. 3-14 for definition of Geometry Vb)

The influence of the skew on the backwater superlevation ratio along the center-line ( $h_1^*/Y_n$ ) has been investigated for skew angles of  $\phi_2 = 15^\circ$  and  $30^\circ$ . Figures 7-7-1 and 7-7-2 give the backwater superlevation  $h_1^*/Y_n$  as a function of  $(F_n/M)^2$  for the two skew angles tested. A summary of these results is given in Fig. 7-7-3.

The raw and calculated data for Geometry Vb are given in Table 7-7.



VII-3 Geometry VI Two-Span Semi-Circular Arch Bridge Constrictions Tests by T.P. Chang  
 (See Fig. 3-14 for definition of Geometry VI)

The pier width,  $P$ , used in the models was equal to one third of the span or  $b/3$ . (A different pier width was used for submerged tests.) The influence of this type of constriction on the backwater superlevation ratio has been investigated for 3 values of the channel width ratio  $M = 0.3; 0.5$  and  $0.7$ .

The backwater superlevation ratio  $h_1^*/I_n$  was plotted vs.  $(F_n/M)^2$  in fig. 7-8-1, and the equation of the least square fit line is given in the figure. The values of the head loss coefficient  $K$  are plotted vs. the channel opening ratio  $M^3$  in fig. 7-8-2, and the equation of the line obtained by the least square method is given in the figure. The values of the backwater ratio coefficient  $D$  are given in fig. 7-8-3.

The raw and calculated data for Geometry VI are given in Table 7-8.





VII-9 Geometry VII-Two-Dimensional Circular Segment Arch Bridge Constrictions  
Tests by T. P. Chang  
 (See Fig. 3-14 for definition of Geometry VII)

The influence of the amount of depression of the center of the arch with respect to the bottom of the stream, (as given by  $\beta = d/r$ , where  $d$  the distance between the channel bottom and the center of the circular segment of radius  $r$ ) on the backwater superelevation ratio has been investigated for 3 values of the depression parameter  $\beta = 0; 0.3$  and  $0.5$ .

The values of the backwater superelevation ratio  $h_1^*/Y_n$  have been plotted vs.  $(F_n/M^2)^2$  in figures 7-9-1 to 7-9-3 for the three values of the depression parameter. In each figure the equation of the least square fit has been given. A summary of the results is given in fig. 7-9-4.

Values of the head loss coefficient  $K$  are plotted vs. the channel opening ratio  $Y_n$ , for the three values of the depression parameter tested, in figures 7-9-5 to 7-9-7. In each figure the equation of the least square fit straight line is given. A summary of the head loss coefficient values is given in fig. 7-9-8.

The values of the backwater ratio coefficient are given in figures 7-9-9 to 7-9-11.



# VII-10 Bibliography of Chapter 7

1. Bakmeteff, B., "Hydraulics of Open Channels", McGraw-Hill 1932.
2. Powell, R. W. and Posey, C. J., "Resistance Experiments in a Triangular Channel", Journal of the Hydraulics Division, Proceedings ASCE, May 1959.
3. Lansford, W. M., Robertson, J. M., Discussion, Trans., ASCE, Vol. 123, 1958, p. 707.
4. Owen, W. M., "Laminar to Turbulent Flow in Wide Open Channel", Trans. ASCE, vol. 119, 1954.
5. Tracy, H. J., Garter, R. W., "Backwater Effects of Open Channel Constrictions", Trans. ASCE 120, 1955.
6. Henry, H. R., Discussion on "Diffusion of Submerged Jets", Trans. ASCE, vol. 115, 1950, p. 687-694.
7. Liu, H. K., Bradley, J. N. and Plate, E. J., "Backwater Effects of Piers and Adjustments", Colorado State University, GER57HKLIO, Oct. 1957.
8. Lipka, J. "Graphical and Mechanical Computation", p. 140-141.



## VIII SUBMERGED FLOW TESTS RESULTS - Tests by O. Ekkeri

VIII-1 Test Selection

The selected models were to be tested in the 64 foot long flume, first with smooth and then with rough boundaries. The large number of variables involved made it necessary to establish a systematic procedure for selecting the quantities allowed to vary and those held constant in the several tests so that the possible range of the variables could be covered uniformly and completely. This was of concern because the range of discharges and slopes for which submergence could be attained was very limited. The procedure followed was based on the theoretical analysis and on the testing of simple geometries.

The channel width ratios,  $M' = b/B$  for which submergence was possible with the flow available in the laboratory was determined from preliminary tests. The testing of geometry I-a with the selected channel width ratios gave the flow rates necessary for submergence for each model. The dimensionless discharge  $\frac{Q}{g^{1/2} b^{5/2}}$ , which according to equ. 3-7-33 is related to the backwater ratio  $Y_1/b$ , was calculated for several discharges and channel width ratios to be tested as indicated in the following table.

Q	$\frac{Q}{g^{1/2} b^{5/2}}$				
cfs	M = 0.15	M = 0.20	M = 0.25	M = 0.275	M = 0.30
2.0	0.7095	0.353	0.202	0.159	0.128
2.5	0.885	0.441	0.2525	0.199	0.160
3.0	1.062	0.529	0.303	0.238	0.192
3.5	"	"	0.354	0.278	0.224
4.0	"	"	0.405	0.318	0.256

By choosing flow rates in the test runs that give different values of  $Q/g^{1/2} b^{5/2}$ , grouping of data in the graphs could be prevented. The seven tables that follow this section show the test runs made for the different geometries. The conditions selected





Table I through VII were chosen in part from the table developed in this section.



Table I - Smooth Boundary Tests

$$n = 0.0110$$

Geometry I-a

Flow Rate cfs.	Froude Number $F_n$			Channel Width Ratio (b/B)			
	0.10	0.15	0.20	0.20	0.25	0.275	0.30
2.0	X			X	X	X	X
2.0		X		X	*	*	*
2.0			X	X	*	*	*
2.5	X			O	X	X	X
2.5		X		X	X	X	X
2.5			X	X	X	X	X
3.0	X			O	X	X	X
3.0		X		O	X	X	X
3.0			X	O	X	X	X
3.5							
3.5		X		O	X	X	X
3.5			X	O	X	X	X

X Regular test measurements obtained

O The flow overtopped the model and channel walls

\* Submergence was not possible for these flow conditions





Table II - Smooth Boundary Test

$$n = 0.0110$$

Geometry I-b

Flow Rate cfs.	Froude Number			Channel Width Ratio b/B													
	$F_n$			0.20						0.25						0.30	
	.10	.15	.20	Thickness Factor L/b													
				.25	.50	.75	1.0	.25	.50	.75	1.0	.25	.50	.75	1.00		
2.0	X		X	X	X	X	X	X	X	X	X	X	X	X	X		
2.0		$X_1$	*	*	*	*	*	*	*	*	*	*	*	*	*		
2.0			$X_1$	*	*	*	*	*	*	*	*	*	*	*	*		
2.5	X		O	O	O	O	X	X	X	X							
2.5		X	X	X	X	X	X	X	X	X	X	X	X	X	X		
2.5			X				X	X			X	X	X	X	X		
3.0	$X_1$		O	O	O	O											
3.0		X	O	O	O	O	X	X	X	X	X	X	X	X	X		
3.0			X	O	O	O	O				X						
3.5	$X_1$		O	O	O	O	O	O	O	O							
3.5		X	O	O	O	O	X	X	X	X	X	X	X	X	X		
3.5			X	O	O	O	O			X	X						
4.0	$X_1$		O	O	O	O	O	O	O	O							
4.0		X	O	O	O	O	O	O	O	O			X	X			
4.0			$X_1$	O	O	O	O										

X Regular test measurements obtained

O The flow overtopped the model and channel walls

\* Submergence was not possible for these flow conditions

X<sub>1</sub> Experimental condition investigated



Table III - Rough Boundary Tests

$$n = 0.0238$$

Geometry I-a

Flow Rate cfs.	Froude Number			Channel Width Ratio (b/B)			
	0.10	$F_n$ 0.15	0.20	0.20	0.25	0.275	0.30
2.0	X			X	X	X	X
2.0		X <sub>1</sub>			*	*	*
2.0			X	X	*	*	*
2.5							
2.5		X		X	X	X	X
2.5			X	X	X	X	X
3.5							
3.5		X		O	X		
3.5			X	O			

X Regular test measurements obtained

O The flow overtopped the model and channel walls

\* Submergence was not possible for these flow conditions

X<sub>1</sub> Experimental condition investigated



Table IV - Rough Boundary Tests

$$n = 0.0238$$

Geometry I-b

Flow Rate cfs.	Froude Number $F_n$			Channel Width Ratio (b/B)								Thickness Factor (L/b)			
	.10	.15	.20	0.20		0.25		0.30				.25	.50	.75	1.0
				.25	.50	.75	1.0	.25	.50	.75	1.0				
2.0	X			X			X	X			X				X
2.0		$X_1$						*	*	*	*	*	*	*	*
2.0			X	X	X		X	*	*	*	*	*	*	*	*
2.5	$X_1$			0	0	0	0								
2.5		X		X		X	X	X		X	X	X	X	X	X
2.5			X	X		X	X				X				X
3.5	$X_1$			0	0	0	0	0	0	0	0				
3.5		X		0	0	0	0	X	X		X				
3.5			$X_1$	0	0	0	0								

X Regular test measurements obtained

0 The flow overtopped the model and channel walls

\* Submergence was not possible for these flow conditions

 $X_1$  Experimental condition investigated





Table V - Rough Boundary Tests

$$n = 0.0238$$

Geometry V-b

Flow Rate cfs.	Froude Number			Thickness Factor $L/b = 0.50$ Channel Width Ratio ( $b/B$ )						
	.10	$F_n$ .15	.20	0.20			0.30			
				Angles of Skew $\alpha_2$						
				15°	22½°	30°	15°	22½°	30°	
2.0	X			X	X	X		X	X	
2.0		X		X	X	X	X	*	*	
2.0			X	X	X	X	*	*	*	
3.0	X			X		X	X		X	
3.0		X		X		X	X		X	
3.0			X	X		X	X		X	

X Regular test measurements obtained

O The flow overtopped the model and channel walls

\* Submergence was not possible for these flow conditions



Table VI - Rough Boundary Tests

$$n = 0.0238$$

Geometry VI

Flow Rate cfs.	Froude Number $F_n$			Thickness Factor $L/b = 0.50$ Channel Width Ratio $b/B$		
	.10	.15	.20	.15	.20	.25
2.0	X			X	X	X
2.0		X		X	X	*
2.0			X	X	X	*
2.5	X			X	X	X
2.5		X		X	X	X
2.5			X	X	X	*
3.0	X			X	X	X
3.0		X		X	X	X
3.0			X	X	X	X

X Regular test measurements obtained

O The flow overtopped the model and channel walls

\* Submergence was not possible for these flow conditions





Table VII - Rough Boundary Tests

$$n = 0.0238$$

## Geometry VII

Flow Rate cfs.	Froude Number $F_n$					Channel Width Ratio $b/B$					
	.1	.2	.3	.4	.5	= 0	0.35 = .3	= .5	= 0	0.50 = .3	= .5
1.0	X					*		X	*	*	
2.0	X					*	X		*	*	X
2.0		X				*	X		*	*	X
2.0			X			*	X		*	*	X
2.0				X		*			*	*	X
2.0					X	*			*	*	X
2.5	X					X			*		
2.5				X		*	X		*	*	
2.75					X	*	X		*	*	
3.0	X									X	
3.0		X				X				*	X
3.85	X							O	X		
3.85		X						O	*	X	
3.85			X			X		O	*	*	X
3.85				X		X		O	*	*	X
3.85					X	X		O	*	*	X

X Regular test measurements obtained

O The flow overtopped the model and channel walls

\* Submergence was not possible for these flow conditions



## 11-2 Definitions: Fully Submerged and Partly Submerged Flow

The terms free outflow, fully submerged and partly submerged outflow are frequently used in this chapter and are defined as follows. Free outflow exists when the jet discharging from the downstream face of the bridge opening is surrounded, except for the channel bottom, only by air and a hydraulic jump occurs further downstream. Fully submerged outflow exists when the jet discharges into a stream that has a depth equal to or greater than the downstream height of the bridge opening. Partly submerged outflow is the case when the jet discharges into a stream that has a depth less than the height of the bridge opening and no downstream jump occurs.

The terms free outflow, fully submerged and partly submerged outflow are commonly used in this chapter and are defined as follows. Free outflow occurs when the jet discharging from the downstream face of the bridge opening is submerged except for the channel bottom, only by air and a hydraulic jump occurs further downstream. Fully submerged outflow exists when the jet discharges into a stream that is a depth equal to or greater than the downstream height of the bridge opening. Partly submerged outflow is the case when the jet discharges into a stream that is a depth less than the height of the bridge opening and no downstream jump occurs.

### VIII-3 Geometry Ia - Smooth Boundaries (See fig. 3-14 for definition of Geometry Ia)

#### a) Coefficients of Contraction, of Discharge and of Velocity for Free Jet Outflow

In order to investigate the coefficients of velocity, contraction and discharge for submerged bridge inlets, 67 test runs were made (see Table I - VII). The coefficients are defined as follows: Coefficient of contraction,  $C_c$ , is the ratio of jet area at vena contracta  $A_v$  to the area of the orifice  $A_o$ .

$$C_c = \frac{A_v}{A_o}$$

Coefficient of discharge,  $C_d$ , is the ratio of the actual discharge  $Q_a$ , obtained from the Venturimeter reading, to the theoretical  $Q_t$ , as calculated by formula

$$C_d = \frac{Q_a}{Q_t}$$

Coefficient of velocity is the ratio of actual velocity  $V_a$  to the theoretical velocity

$$C_v = \frac{V_a}{V_t}$$

It is customary to combine the three coefficients as follows: From continuity equation the following can be written:

$$\frac{Q_a}{Q_t} = \frac{A_v}{A_o} \frac{V_a}{V_t}$$

from which it follows that:

$$C_d = C_c C_v$$

To find the coefficient of contraction the vena contracta had to be located and the cross-sectional area measured. This was done by means of the electronic point gauge.

A sufficient number of readings were taken at the vena contracta to plot the cross sectional area on graph paper. By use of a planimeter the area  $A_v$  was obtained and the coefficient of contraction could be calculated, as the area of the model opening was known.





The coefficient of contraction was plotted versus the ratio  $b/Y_1$  of the model opening width to the backwater depth using the channel width ratio  $b/B$  as parameter (see Figure 8-3-1).

To obtain values for the calculation of the coefficient of discharge  $C_d$ , a theoretical discharge equation was developed. The development of this equation (3-7-26) was presented in the theoretical analysis in Chapter III. The actual rate of flow through the constriction was obtained from the manometer readings and the venturi meter calibration curves. Curves were plotted for the coefficient of discharge  $C_d$  versus the ratio  $b/Y_1$  and the channel width ratio was again used as parameter (see Figure 8-3-1). The coefficient of velocity was then found from the relationship between the three coefficients,  $C_d = C_c C_v$  and plotted versus  $b/Y_1$  in Figure 8-3-1.

The  $C_d$  curves seem to converge toward the value 0.61 as the  $\frac{b}{Y_1}$  ratio tends to zero. The curves are closely spaced straight lines and the  $C_d$  values decrease with increasing channel width ratios. The  $C_c$  curves also tend towards the 0.61 value as the  $\frac{b}{Y_1}$  ratio decreases. Values of  $C_c$  decrease for increasing channel width ratios. For increasing  $C_c$  values, within the test range, the  $C_c$  curves tend to increase toward the value 0.71 and then stabilize at this value. The  $C_v$  curves have the same relative spacing as the  $C_c$  and  $C_d$  curves as to the  $\frac{b}{B}$  ratio but tend toward the value 1.0 as a limiting value when the  $\frac{b}{Y_1}$  ratio decreases toward zero.

The test data are recorded in test runs 1 - 67 shown in Table 8-1. The calculated values to find  $C_c$ ,  $C_d$  and  $C_v$  are found in Table 8-4.

#### b) Velocity Distribution at Vena Contracta for Free Jet Outflow

Extensive velocity measurements were taken in the jet downstream of constriction at the vena contracta in order to observe the velocity distribution. The Prandtl tube together with the pressure transducer were used. The readings were taken in a grid system to obtain full coverage over the cross section. The borderline of the area at the cross-section was also measured and plotted on graph paper together with the velocity grid values. From this the isovelocity curves were drawn. Figure





8-3-2 shows one of the typical isovelocity curves drawn from such grid measurements. Figure 8-3-3 shows the result obtained by following the individual isovelocity curves in the water cross-section itself. This was done by moving the Prandtl tube through the cross-section and mapping the path for the individual isovelocity curves obtained by means of the horizontal and vertical traversing devices. The data of Figures 8-3-2 and 8-3-3 correspond to discharges 3.75 cfs and 2.62 cfs, normal depth Froude number 0.142 and 0.108 and opening ratios 0.30 and 0.30 respectively.

In Figure 8-3-4 the values of the velocities are plotted at different depths and a mean velocity curve is drawn. The data for Figure 8-3-4 are the same as those for Figure 8-3-3. Figure 8-3-4 shows the velocity variation over the opening width at different depths. A similar study was made for other flow conditions as recorded in Table 8-3. All the recorded values when plotted, show the same characteristic velocity distribution as shown in Figures 8-3-2 to 8-3-4.

#### c) The Generalized Backwater Equation - Outflow Fully and Partly Submerged

From the theoretical analysis done in Chapter III it is expected that the general relation between the backwater and normal depth is of the form

$$\frac{Y_1}{Y_n} = C \left[ \left( \frac{F_n}{M^0} \right)^2 \right]^{\gamma'} \quad (8-3-1)$$

where C is a coefficient that would take into account the effects of the approach velocity, discharge coefficient, non-hydrostatic pressure distribution, non-uniform velocity distribution and other empirically determined factors. In a logarithmic plot of  $Y_1/Y_n$  versus  $(F_n/M^0)^2$ , the slope of the line is  $\gamma'$ . A total of 33 tests were made on geometry I-a and processed on the IBM 1620 computer to obtain plotting values of  $(Y_1/Y_n - 1)$  versus  $(F_n/M^0)^2$ . The graph is shown on figure 8-3-5. From this graph the values  $\gamma'$  and C were found to be 0.90 and 1.18 respectively, and equation 8-3-1 can be written for the submerged conditions of geometry I-a in the following way:

$$\frac{Y_1}{Y_n} = 1 + 1.18 \left[ \left( \frac{F_n}{M^0} \right)^2 \right]^{0.90} \quad (8-3-2)$$





or

$$\frac{Y_1}{Y_n} = 1 + 1.18 \left( \frac{F_n}{M^2} \right)^{1.80} \quad (8-3-3)$$

The test data taken to obtain this generalized backwater equation 8-3-3 are recorded in test runs 102-134 which are located in Table 8-2. The calculated values from the data are presented in Table 8-3. A least square fitting of the backwater ratio points for fully submerged flow is given in Fig. 8-10-1. The values of the head loss coefficient  $K$  are given in Fig. 8-9-1.

A general backwater equation was not obtainable for the free jet outflow. This is because the Froude numbers for test runs 1-67 are all in the range of  $0.550 - 0.587$  which results in one group of numbers, and a line could not be defined.

#### d) Discharge Coefficient for Free, Submerged and Partly Submerged Outflow

A graph was made of the discharge coefficient,  $C_d$ , versus the channel opening ratio,  $M^2$ , for the submerged smooth bridge opening, Geometry I-a (Figure 8-3-6/). The curves obtained are for the submerged discharge jet except for the two upper most curves which are for partly submerged jets. These curves are similar to those estimated by P. F. Biery (see Art. VII-1-c) for the unsubmerged case and for channel opening ratios of 0.29 and up. The present values for the submerged case were obtained for the range of  $M^2$  between 0.10 and 0.35. Figure 8-3-6 shows the  $C_d$  versus  $M^2$  curves for submerged and partly submerged flow as well as Biery's discharge coefficient curves for the unsubmerged case which have been superposed for the purpose of comparison. The test data taken to obtain the curves in Figure 8-3-6 are recorded in test runs 102 to 134 which are located in Table 8-2. The calculated values are presented in Table 8-4.

The values of the discharge coefficient are summarized in Figure 8-3-7. For the submerged jet, two sets of curves are given, one uses the Froude number as a parameter, the other uses the ratio  $Y_n / \frac{b}{2}$  of the normal depth to the arch radius. The free jet discharge coefficient curves previously presented in Figure 8-3-1 have been reproduced here for completeness. The calculations are shown in Table 8-4.



#### VIII-4. Geometry I-b - Smooth Boundaries

As can be seen from the definition of test geometries, (fig. 3-14) geometry I-a is a special case of geometry I-b. By setting the variable  $\frac{L}{b}$  equal to zero in the definition of geometry I-b, the geometry I-a is obtained. Geometry I-a therefore represents the limiting case of geometry I-b, and can be treated together with I-b.

In the theoretical analysis made in Chapter III the dimensionless relation

$$\frac{Q}{g^{\frac{1}{2}} b^{5/2}} = f\left(\frac{L}{b}\right) \quad (8-4-1)$$

was developed for the orifice type flow through a submerged arch constriction. A total of 92 test runs were conducted for submerged conditions in the smooth channel. Three sets of dimensionless curves were plotted. To save space and make it easier to compare the curves, they were all plotted in one figure. The  $\frac{L}{b}$  ratio is used as parameter, and the Froude number is constant for each set of curves. To be able to show all three sets of curves clearly on one graph, the vertical coordinate axis was broken into three parts each starting from zero. The curves are shown in Figure 8-4-1. For higher Froude numbers the curves get closer spaced. This means that the  $L/b$  ratio becomes insignificant for all practical purposes when the Froude number reaches a value of about 0.20 for the smooth ( $n = 0.0110$ ) boundary case of geometry I-b. The data from the 92 test runs are listed in run number 101-192 and recorded in Table 8-2. The calculated values of the plotted points are shown in Table 8-4.

The backwater superlevation ratio  $h_1^*/Y_n$  is plotted vs.  $(F_n/M^*)^2$  for values of the length parameter  $L/b = 0.25; 0.50; 0.75$  and  $1.0$  in figures 8-10-2 to 8-10-5. The equations of the lines obtained by least squares are given in the figure. Figure 8-10-6 summarizes the backwater superlevation data for geometries Ia, and Ib with smooth boundaries. The values of the head loss coefficient  $K$  and the lines obtained by least square fitting are given in figures 8-9-2 to 8-9-5 for the same values of the length parameter  $L/b$ . A summary of the head loss coefficients for geometries Ia and Ib with smooth boundaries is given in Fig. 8-9-6.





### VIII-5 Geometries I-a and I-b - Rough Boundaries

#### a) Test Data

A total of 38 test runs were made in order to plot the dimensionless curves shown in Figure 8-5-1. These three sets of curves were also based on the dimensionless equation 3-7-33 developed in Chapter III. The data are recorded in test runs 193-231 and can be found in table 2-2. The calculated values from the data are listed in Table 8-4.

The values of the backwater superlevation ratio  $h_1^*/Y_n$  were plotted vs.  $(F_n/M)^2$  for the five values of the length parameter tested ( $L/b = 0; 0.25; 0.50; 0.75; 1.00$ ) in figure 8-10-7. The lines were fitted by eye, and their equations are given in the figure. The values of the discharge coefficient were plotted vs. the channel opening ratio in fig. 8-9-7 for the same values of the length parameter. The equations of the lines fitted by eye are given in the figure.

The investigation shows that the width of the constriction in the direction of flow,  $L$ , influences the backwater to a certain degree when the Froude number is low. The wider the bridge in the direction of flow, the lower is the backwater depth obtained. For a Froude number of 0.15 the backwater ratio for an  $L/b$  ratio of 1.0 was as much as 30% lower than for a  $L/b$  ratio of 0.00. For the more practical cases where the  $Y_1/b$  ratio is in the order of about 0.50 to 1.00, a lowering of about 10-20% in the backwater ratio is usual when the  $L/b$  ratio is increased from 0.00 to 1.00. Flow through three dimensional arch bridges is very similar in behavior to the flow through short culverts. For short culverts, the flow characteristics are relatively independent of the slope and the factors that involve the length are comparatively unimportant. The control section for square edge openings, such as investigated here, is at the inlet.

Separation of flow around the opening, at the inlet section, was frequently observed. The flow contracted towards vena contracta section in the first part of the barrel expanded in a spiral motion as shown in Figure 8-5-2 and ended in a slug flow at the submerged outlet. Figure 8-5-3 shows the case where slug flow occurs at





the exit of the barrel. Figure 8-5-4 presents the free jet case for geometry I-a with rough boundaries and the same flow.

Vortex action was also often observed. This air-vortex occurs from the surface right above the crest of the inlet and introduces air through the opening. This decreases the water area of the opening and hence the flow through the constriction, and as a result the backwater increases.

An important effect upon the separation phenomena, that controls the change of flow from a sluice type to full conduit flow, is the existence of a negative pressure in the barrel. This is caused by the relative magnitudes of air inflow from the outlet and from the vortex action over the inlet. The outflow of air due to entrainment at the air-water surface also has an effect upon the separation phenomena, the more air entrained the less separation will occur and the barrel will tend towards full conduit flow.

#### c) Comparison Between Smooth and Rough Boundary Tests

A comparison between the limiting curves of Figures 8-4-1 and 8-5-1 for the smooth and rough boundary conditions respectively are made in Figure 8-5-5. These curves show that a rough boundary condition is of advantage for higher Froude numbers ( $F_n > 0.15$ ) as could be expected from observing the flow behavior. For higher Froude numbers the approach velocities will increase and consequently give a higher turbulence level due to the natural roughness. This will improve the ability of the barrel to produce full conduit flow, because it increases the air entrainment in the barrel at the air-water surface and hence reduces the separation at the inlet.



# VIII-6 Geometry V-b Three-Dimensional Skewed Bridges - Rough Boundaries (See Fig. 3-14 for definition of geometries)

The discharge jet shoots to the side of the flume in a direction approximately perpendicular to the face of the bridge.

The test results are presented in the dimensionless performance curves in Figure 8-6-1, based on the theoretical equation 3-7-33 developed in Chapter III. Three sets of curves are plotted using the Froude number and the angle of skewness,  $\phi_2$ , as parameters. The width ratio,  $L/b$  is kept constant at the value  $L_0/b = 0.50$ . The performance curves show that a variation in the angle of skew between  $\phi_2 = 15^\circ$  and  $\phi_2 = 30^\circ$  is a relative unimportant factor compared to the effect of a change in the Froude number. To be noted is also the better performance of these skewed bridge constrictions for low Froude numbers, ( $F_n = 0.10$ ) compared to the  $\phi_2 = 0.0$  constriction of Geometry I-b. The explanation may be that the non-symmetry of the skewed bridge constriction generates more turbulence in the flow at the inlet and hence a flow condition closer to conduit flow, at a lower Froude number. As the Froude number increases and both Geometries, I-b and V-b, agitate about the same amount of turbulence in the flow, the difference in the performance curves decreases. The part of the curves having a  $X_1/b$  ratio less than about 0.5 do not pertain to the submerged inlet case, but are merely an expected trend of the curves for the free surface flow. A total of 24 test runs were made on the skewed bridges. They are recorded in Table 8-2 as test run numbers 232 to 255. The calculated data to plot the curves are listed in Table 8-4. The values of the backwater superlevation ratio  $h_1^*/I_n$  were plotted vs.  $(F_n/M^0)^2$  in Figure 8-10-3. The equation of a visual fit line is given on the figure. The values of the discharge coefficient  $K$  are plotted vs. the channel opening ratio in Fig. 8-9-8. The equation of a visual fit line is given on the figure.

The following table shows the results of the tests in a typical experiment.

Experiment 1: The effect of the angle of the plate.

The test results are presented in the following table.

Table 1: Results of the tests for Experiment 1.

Two sets of curves are plotted using the same method as the table of results.

As previously, the same method is used to plot the results of the tests.

The performance curves show that the results are significantly different.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.

The results are plotted on the same graph as the results of the tests.



VIII-7 Geometry VI - Two Span Semicircular Arch Bridge Constriction Rough Boundaries  
 (See Fig. 3-14 for definition of geometries)

This geometry represents about 11% of all existing arch bridges in the state of Indiana. The great majority of these bridge constrictions have a thickness factor,  $L/b$ , of about 0.50 which was chosen for the experimental models of Geometry VI.

The test results are presented in the dimensionless graphs shown in Figure 8-7-1. To be noted is that the opening width of the models,  $b$ , is the width of one of the openings. The performance of the models in Geometry VI is approximately the same as for Geometry I-b of same thickness factor.

A total of 27 test runs were made and the data taken are recorded in test runs no. (256-282) as shown in Table 8-2. The calculated values are presented in Table 8-5. The values of the backwater superelevation ratio  $h_1^*/Y_n$  were plotted vs.  $(F_n/M^0)^2$  in fig. 8-10-9. The equation of a visual fit line is given on the figure. The values of the discharge coefficient  $K$  are plotted vs. the channel opening ratio  $M^0$  in Fig. 8-9-8. The equation of a visual fit line is given on the figure.



III-8 Geometry VII - Segment Arch Bridge Rough Boundaries  
 (See Fig. 3-14 for definition of geometries)

With reference to Figure 3-12, it is readily seen that the dimensionless relationship of the discharge as a function of the backwater depth and the width of the constriction holds true also for the segment arch openings. The curves shown in Figure 8-8-1 are based on this relationship as expressed in Equation 3-7-33, derived in Chapter III. A total of 22 test runs (No. 285 to 307) were done and recorded in Table 8-2. The calculated values are found in Table 8-5.

Figure 8-8-1 shows that the spacing between the curves becomes very small as the Froude number increases beyond 0.3. This means that the Froude number becomes insignificant as a parameter when the degree of turbulence increases beyond a certain value ( $F_n > 0.3$ ).

The values of the backwater superlevation ratio  $h_1/Y_n$  were plotted vs.  $(F_n/M^2)^2$  in fig. 8-10-10. The equation of a visual fit line is given in the figure. The values of the discharge coefficient  $K$  are plotted vs. the channel opening ratio  $M^2$  in fig. 8-9-10. The equation of a visual fit line is given in the figure.

with reference to Figure 7-10. It is possible that the

relationship of the relationship is a function of the relationship

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

relationship being used. The relationship is a function of the

### VIII-9 Head Loss due to Submerged Arch Bridge Constrictions

In the theoretical analysis in Chapter III an expression for the additional head loss coefficient due to the bridge constriction was found, equation (3-8-13).

Assuming  $\alpha_1 = \alpha_4 = \alpha$ , then

$$K = \frac{h_1^*}{V_0^2/2g} = \alpha \left[ \left( \frac{A_0}{A_y} \right)^2 - \left( \frac{A_0}{A_1} \right)^2 \right] \quad (3-8-14)$$

This equation, which holds for submerged bridge constrictions is similar to the one for free surface flow through a bridge constriction, and K varies primarily with

- The channel opening ratio  $M^0$
- Type and shape of bridge constriction such as inlet shape, wing wall angle  $\phi_1$ , skewness angle  $\phi_2$  and thickness factor,  $L/b$
- Number of bridge spans, N
- Eccentricity of bridge opening, e
- Froude number  $F_n$

The head loss coefficient K was computed on the IBM 7090 from equation 3-8-14.

The corresponding value of the channel opening ratio,  $M^0$ , was also computed, and by a least mean square routine the slope of the line of the plot K versus  $M^0$  was found in arithmetic scale. A significant value such as  $L/b$ ,  $\phi_2$  and N was used as parameters both for smooth and rough boundary tests. The plot of these curves are shown in Figures 8-9-1 to 8-9-10.

For the smooth boundaries a sufficient number of data was available to use the least square method on the computer. In the case of rough boundaries, however, the data available for each parameter were not always sufficient and some of the lines had to be fitted by eye.

The data used for the calculations are listed in runs 121-306 presented in Table 8-2. The calculated values from the computer are listed in tables 8-4 and 8-5.



In the theoretical part of the ...

$$\text{Equation (1) } \dots$$

$$\dots$$

It is evident that ...

- a) The first ...
- b) The second ...
- c) The third ...
- d) The fourth ...
- e) The fifth ...
- f) The sixth ...
- g) The seventh ...
- h) The eighth ...
- i) The ninth ...
- j) The tenth ...

The last part of the ...

and more ...

It is ...

For the ...

and ...

The data ...

2. The calculated ...

# VIII-10 General Backwater Equations for Geometries I-a, I-b, VI and VII - Smooth and Rough Boundaries

The theoretical development of these equations was done in Chapter III. The generalized backwater equation is of the form

$$\frac{Y_1}{Y_N} = C \left[ \left( \frac{F_N}{M^0} \right)^2 \right]^{\delta} \quad (8-10-1)$$

However, it was found more convenient to plot the test results for the fully submerged discharge jet in the form

$$\frac{Y_1}{Y_N} - 1 = C \left[ \left( \frac{F_N}{M^0} \right)^2 \right]^{\delta} \quad (8-10-2)$$

If  $h_1^*$  is substituted for  $Y_1 - Y_N$ , equation 8-10-2 can be written in the following form:

$$\frac{h_1^*}{Y_N} = C \left[ \left( \frac{F_N}{M^0} \right)^2 \right]^{\delta} \quad (8-10-3)$$

This is the presentation used in the graphs at the end of this section. Figures 8-10-1 to 8-10-10 present the generalized backwater equations for the geometries considered. Significant values of the geometries are used as parameters.

Values for  $\frac{h_1^*}{Y_N}$  and  $\left( \frac{F_N}{M^0} \right)^2$  were calculated in the same computer program as used for the head loss considerations in the previous section. These points were to be plotted on a log log scale, so the computer program was also written to determine the slope of the best fitting line through these points. A least mean square routine for log log plots was used. For the smooth boundaries a sufficient number of data was available to use the least square method in finding the slope of the line. In the case of rough boundaries, however, it was sometimes necessary to fit the lines by eye from the few data available.

The data used for the calculations are listed in runs 101-306, presented in table 8-2. The calculated values are listed in tables 8-4 and 8-5.

There are some advantages in doing all these calculations in one computer program. Only one set of data has to be prepared and the computer stores the values in the memory once. The computer time used, therefore, becomes a minimum. For all the

The theoretical development of time-dependent perturbation theory is based on the following equation:

$$i\hbar \frac{d}{dt} \psi = (H_0 + V) \psi$$

where  $\psi$  is the wave function,  $H_0$  is the unperturbed Hamiltonian, and  $V$  is the perturbation. The equation is solved by the method of variation of constants.

$$\psi = \sum_n c_n(t) \psi_n$$

where  $\psi_n$  are the eigenfunctions of  $H_0$  and  $c_n(t)$  are the coefficients to be determined. The equation is then solved by the method of variation of constants.

$$c_n(t) = c_n(0) e^{-iE_n t/\hbar}$$

where  $E_n$  are the eigenvalues of  $H_0$  and  $c_n(0)$  are the initial coefficients. The equation is then solved by the method of variation of constants.

$$c_n(t) = c_n(0) e^{-iE_n t/\hbar}$$

where  $E_n$  are the eigenvalues of  $H_0$  and  $c_n(0)$  are the initial coefficients. The equation is then solved by the method of variation of constants.

The equation is then solved by the method of variation of constants. The equation is then solved by the method of variation of constants.

The equation is then solved by the method of variation of constants. The equation is then solved by the method of variation of constants.

The equation is then solved by the method of variation of constants. The equation is then solved by the method of variation of constants.

The equation is then solved by the method of variation of constants. The equation is then solved by the method of variation of constants.

The equation is then solved by the method of variation of constants. The equation is then solved by the method of variation of constants.

calculations pertaining to the figures 8-9-1 to 8-10-10, the time used by the IBM 7090 was less than 10 minutes.





## VIII-11 Conclusions - Submerged Tests

The results of this report are applicable to bridges with submerged inlet and geometries I-a, I-b, V-b, VI and VII (see definition of geometries in Chapter III and figure 3-14.) No eccentricity, entrance rounding or wing walls are counted for.

Findings were the following:

1. Equation of discharge for orifice type flow through a semi-circular submerged arch bridge constriction.
2. Semi-empirical expression for the occurrence of free surface flow and orifice type flow through the bridge opening.
3. Graphs presenting the discharge as a function of the ratio of the backwater depth to the arch span.
4. Graphs showing the ratio of the backwater to the normal depth as a function of the normal depth Froude number and the channel opening ratio.
5. Empirical generalized backwater equations derived for the several geometries from the graphs in point 4.
6. Graphs giving the values of the constriction head loss coefficient as a function of the channel opening ratio for the different test geometries.

### Conclusions

1. The backwater at submerged arch bridge constrictions perpendicular to the stream decreases as the length of the bridge in the direction of flow increases.
2. For equal bridge length the backwater due to submerged arch bridges is further decreased when the constriction is skewed with respect to the direction of flow, at least for skew angles up to  $30^\circ$ .
3. The value of the head loss coefficient due to a submerged arch bridge constriction is independent of the normal depth Froude number as long as both inlet and outlet of the bridge are submerged.

The results of this report are applicable to bridges with submerged intakes. Geometric I-a, I-b, V-b, VI and VII (see definition of Geometric in Chapter 1 and Figure 3-1a). No asymmetry, entrance rounding or other walls are present.

Findings were the following:

1. Expansion of discharge for outlet type flow through a semi-circular arch bridge.
2. Semi-empirical expression for the occurrence of flow separation from the arch.
3. Graphs presenting the discharge as a function of the angle of the arch to the arch span.
4. Graphs showing the ratio of the discharge to the normal depth for the normal depth from the normal depth from the arch.
5. Empirical generalized correlation with the normal depth from the arch.
6. Graphs giving the values of the coefficient of discharge for the arch.

### References

1. The discharge at submerged arch bridge contraction and expansion.
2. For equal bridge length the discharge is not affected by the discharge.
3. The value of the head loss coefficient due to a submerged arch bridge is independent of the normal depth from the arch.
4. The discharge at submerged arch bridge contraction and expansion.

4. For hydraulically short submerged arch bridges (that is where the barrel is not sufficiently long to allow the expanding depth of flow below the contraction to raise and fill the barrel), the backwater depth increases for an increase in the normal depth Froude number.

5. To obtain a minimum backwater depth at a submerged arch bridge constriction the barrel should flow full (full conduit flow).

For identifying these specimens the following data are given:  
of sufficiently long to show the repeating pattern of the surface  
lines and fill the cavity, the thickness being increased for an increase in the  
of depth inside member.  
To obtain a minimum thickness, depth of a specimen with surface irregularities  
must be about 1/2 inch (12.7 mm).

## IX FIELD WORK

IX-1 A Preliminary Field Survey of Sites for Model-Prototype Comparison of the  
Hydraulics of Arch Bridge Constrictions  
by T. P. Chang and J. T. StrangeINDIANA FLOOD CONTROL AND WATER RESOURCES COMMISSION  
INDIANAPOLIS, INDIANAIntroduction

A series of model-testing studies of the hydraulics of semicircular arch constrictions have been made during the past four years at the Hydraulic Laboratory of Purdue University, under the guidance of Professor Delleur and Professor Toebes. The Indiana Flood Control and Water Resources Commission has been requested to make a field check of some of the arch bridges in Indiana so that a suitable arch bridge, either one-span or two-span, may be selected in order to make model-prototype comparisons by taking field measurements during a flood.

The preliminary field reconnaissance work started in the middle of October of this year. More than 130 arch bridges, both one-span and two-span, have been checked. Ten of these bridges; eight one-span and two two-span, have been chosen for further investigation. Preliminary surveys and photographs have been taken for these ten arch bridges.

Criteria Used for the Selection of Bridge Sites

## 1. Location:

For the convenience of future field measurements during a flood, the bridges should be as close to Indianapolis as possible. For this reason, the field reconnaissance was limited to Marion, Hendrick, Morgan, Johnson, Shelby, Hancock, Hamilton and Boone Counties.

## 2. Channel Condition:

(a) The channel reach close to the bridge site, both upstream and downstream, should be as clear as possible so that the flow during the flood will not be unduly disturbed.



A Preliminary Field Survey of the  
Influence of the  
by T. P. Chang and J. Y. Chang

INSTITUTE OF BOTANY AND ZOOLOGY, NATIONAL TAIWAN UNIVERSITY  
TAIPEI, TAIWAN

Abstract

A series of model-building studies of the influence of the  
institutions have been made during the last four years at the National  
Taiwan University, under the guidance of Professor Chang. The  
National Field Survey and other researches have been made  
which show that the influence of the field survey is  
that the model is not only a model but also a model  
as by using field and laboratory studies.

The preliminary field study was made in the field  
years. The field study was made in the field  
of the field study which was made in the field  
investigation. The field study was made in the field  
in the field.

Introduction

1. Introduction

The introduction of the field study was made in the field  
which was made in the field. The field study was made in the field  
which was made in the field. The field study was made in the field  
which was made in the field.

2. General Introduction

(a) The general introduction to the field study was made in the field  
which was made in the field. The field study was made in the field  
which was made in the field. The field study was made in the field  
which was made in the field.

(b) The cross sections of the channel reach, both upstream and downstream from the bridge, should be uniform in order to avoid the effect of head loss due to enlargement and contraction, and the water should be confined within the stream banks during the flood.

(c) The channel reach should be nearly straight. There should be no confluence close to the bridge.

(d) The shape of the channel cross sections should have as few irregularities as possible.

(e) There should be no structures, such as other bridges, dams, weirs, etc., near the bridge site.

(f) Bridge skew should not be excessive. Skewed bridges, in which the center line of the openings are not parallel with the direction of the channel, should be avoided.

### 3. Arches of the Bridges:

(a) The shape of the arch should be close to semicircular or a part of a circular arch.

(b) The opening ratio of the arch should be small enough to produce an appreciable backwater effect.

(c) Excessive eccentricity should be avoided. The arch opening should be symmetrical with respect to the center line of the channel.

### 4. Flow Condition:

(a) Flow velocity during a flood should be great enough to create a relatively high Froude number,  $F = \frac{V_n}{\sqrt{gD_n}}$ .

(b) The drainage basin should be relatively large (about 15 square miles or more) and topographic relief within the basin relatively small in order to produce a flood of sufficient duration so that desired data may be obtained.

(b) The group meeting in the morning room, held between 10 and 11 a.m. from the bridge, during the winter in order to keep the water of fresh food due to the lack of the refrigerator and the water supply be confined within the house during the winter.

(c) The second level should be made straight, there would be no confusion since in the winter.

(d) The third of the house, which would be made as the first investigation of the house.

(e) There should be a third level, which would be made as the first level, which would be made as the first level.

(f) While the house is being made, the house should be made as the first level, which would be made as the first level, which would be made as the first level.

#### Architect of the Building

(g) The house should be made as the first level, which would be made as the first level, which would be made as the first level.

(h) The house should be made as the first level, which would be made as the first level, which would be made as the first level.

(i) The house should be made as the first level, which would be made as the first level, which would be made as the first level.

#### 4. The Building

(j) The house should be made as the first level, which would be made as the first level, which would be made as the first level.

(k) The house should be made as the first level, which would be made as the first level, which would be made as the first level.

(l) The house should be made as the first level, which would be made as the first level, which would be made as the first level.

deducted from the first level.

## Description of the Field Situation

As far as the purpose of this report is concerned, all of the arch bridges which have been inspected can be put into three general classifications. These are; Highway bridges, City bridges and County Road bridges. Each has its general features and problems.

### 1. Highway Arch Bridges:

- (a) Arch shape is excellent, but almost all of them have a very large opening. Flood waters will probably never reach the middle part of the arch. Hence, the arch effect is negligible.
- (b) Usually the road side drainage ditches are near the faces of the bridge, both upstream and downstream. These drainage ditches suddenly enlarge the channel cross section.
- (c) Channels are not very clear or uniform. Channel and bank conditions are such that if flood levels were high enough to produce the desired arch effect, water would spill out into the fields; thereby, greatly changing the shape of the channel cross sections.
- (d) Since the traffic is usually heavy, working conditions on the bridge are not good.
- (e) Usually the length of the arch constriction is relatively long.

### 2. City Arch Bridges:

- (a) Channel conditions are fairly good, especially in the park areas.
- (b) Flood water is confined within the banks. Flood water levels are high enough to produce an arch effect.
- (c) The shape of the arches are not good, either too flat or not semicircular.
- (d) Sewers are in the channel reach close to the bridge or under the bridge. This is a common and serious problem with the city bridges.



As far as the purpose of this report is concerned, all of the above bridges have been inspected can be put into three general classifications, "Type Highway Bridges, City Bridges and County Road Bridges." Each has its own peculiarities and problems.

## 1. Highway Arch Bridges

- (a) Arch shape is excellent, but almost all of them have a very large opening. Fixed water will probably never reach the main part of the arch. Hence, the arch effect is negligible.
- (b) Usually the road side drainage ditches are built on the same side of the bridge, both upstream and downstream. These ditches often suddenly enlarge the channel across section.
- (c) Channels are not very clean or straight. Channel grade conditions are such that it flows faster than high water and produces the desired effect of water flowing into the main channel. Therefore, greatly reducing the stage of the water in the sections.

- (d) Since the traffic is usually heavy, wearing surfaces on the bridge are not good.

- (e) Usually the length of the arch section is sufficient.

## 2. City Arch Bridges

- (a) Channel conditions are fairly good, according to the present conditions.
- (b) Fixed water is confined within the body. Flow velocity are high enough to produce an even flow.
- (c) The shape of the arches are not good, often the arch is semi-circular.

- (d) In some cases the channel width is too small to the bridge or under the bridge. This is a common and serious problem with the city bridges.



### 3. County Road Arch Bridges:

- (a) The openings of the arch are usually small.
- (b) Channels are not uniform and are sometimes choked by brush and small trees.
- (c) Farm fences across the channel near the bridge catch logs and debris which seriously affect the flood flow under the bridge.
- (d) The channel and bridge size is usually smaller than the highway arch bridge or the city arch bridge.

### Conclusion

After three weeks of field inspection of the arch bridges in the eight counties near Indianapolis, the writers are of the opinion that it is extremely difficult to find an arch bridge for the purpose of model-prototype comparison without any defects. However, ten of the most suitable bridge sites have been selected for further investigation. Each one has some good features and some defects. The list of the bridges are as follows:

1. Clay Street, Indianapolis, crossing Pogue Run (Bridge No. 2a)
2. Brookside Parkway, Indianapolis, crossing Pogue Run (Bridge No. 2b)
3. Jefferson Avenue, Indianapolis, crossing Pogue Run (Bridge No. 2c)
4. South Belmont Avenue, Indianapolis, crossing Little Buck Creek (Bridge No. 8a)
5. State Road 100, crossing Williams Creek (Bridge No. 13)
6. Villa Avenue, Indianapolis, crossing Pleasant Run (Bridge No. 15a)
7. Linden Avenue, Indianapolis, crossing Pleasant Run (Bridge No. 15b)
8. State Road 44, crossing Hurricane Creek (Bridge No. 51)
9. White Lick Creek near State Boys School, Plainfield (Bridge No. 59a)
10. Dean Road, Indianapolis, crossing Howland Ditch (Bridge No. 66a)

The complete information for each of the above bridges are compiled on a separate form. A suggestion given by the writers has been made for each of those bridges.

- (a) The openings of the arch are usually small.
- (b) Channels are not uniform and are sometimes choked by brush and small trees.
- (c) Piers fences across the channel near the bridge catch logs and debris which seriously affect the flood flow under the bridge.
- (d) The channel and bridge side is usually smaller than the highway arch bridge or the city arch bridge.

# Location

After three weeks of field inspection of the arch bridges in the eight counties of Indiana, the writers are of the opinion that it is extremely difficult to find an arch bridge for the purpose of model-prototype comparison without going over, far or the most suitable bridge sites have been selected for further study. Each one has some good features and some defects. The list of the bridges is as follows:

1. Gray Street, Indianapolis, crossing Fogus Run (Bridge No. 2a)
2. Brookside Parkway, Indianapolis, crossing Fogus Run (Bridge No. 2b)
3. Holliston Avenue, Indianapolis, crossing Fogus Run (Bridge No. 2c)
4. South Belmont Avenue, Indianapolis, crossing Little Back Creek (Bridge No. 3a)
5. State Road 100, crossing Williams Creek (Bridge No. 3b)
6. Villa Avenue, Indianapolis, crossing Elkhart Run (Bridge No. 3c)
7. Linden Avenue, Indianapolis, crossing Elkhart Run (Bridge No. 3d)
8. State Road 44, crossing Hartsville Creek (Bridge No. 3e)
9. Little Back Creek near State Boys School, Indianapolis (Bridge No. 3f)
10. Dean Road, Indianapolis, crossing Howard Creek (Bridge No. 3g)

The complete information for each of the above bridges are compiled on a separate form. A suggestion given by the writers has been made for each of these

X-2 Summary of Information on Bridge Sites

For each of the ten bridge sites a resume sheet, one plan view and four cross sections were prepared by the Indiana Flood Control and Water Resources Commission. Aerial photographs were made by the State Highway Department of Indiana for nine of these sites. Topographic maps were prepared from these aerial photographs in the Aerial Photo Laboratory, School of Civil Engineering, Purdue University, under the supervision of Professor R. Miles.





# I. OLNEY STREET, INDIANAPOLIS, CROSSING POGUES RUN

## RESUME

- (1) Compiled number of bridge: No. 2a,
- (2) Location: Lat.  $39^{\circ}47'25''$ , Long.  $86^{\circ}06'26''$ , Indianapolis east Indiana, quadrangle sec. 32, T. 16 N., R. 4 E., at bridge on Olney Street, Indianapolis, crossing Pogue Run, eastern central part of Indianapolis.
- (3) Drainage area: 8.7 square miles.
- (4) Tributary to: Tributary to West Fork White River, Wabash River basin.
- (5) Slope of channel: 3.1/1000.
- (6) Bridge type: One-span concrete arch bridge.
- (7) Skew toward upstream:  $2^{\circ}$  L.
- (8) Skew toward downstream:  $25^{\circ}$  L.
- (9) Width of Bridge: 50 feet.
- (10) Clearance of arch opening: 12.7 feet.
- (11) Width between banks of channel: 90 feet.
- (12) Width of channel bottom: 24 feet.
- (13) Eccentricity: Low flow part of channel located at left side of channel. Center line of arch is about 7 feet right of center line of low flow channel, but the arch center line nearly coincides with the center line between the two banks.
- (14) High water mark: 3 feet below top of arch opening but date is uncertain.
- (5) Channel condition:
  - (a) Bend about 175 feet upstream from upstream face of bridge.
  - Bend about 180 feet downstream from downstream face of bridge.
  - (b) Trees and brush distributed along right banks both upstream and downstream.
  - (c) Two 1-foot diameter sewers in upstream side.
  - (d) Channel bottom is irregular.
  - (e) A bridge on Sherman Drive located 1,500 feet upstream from this site.
  - A bridge on Brookside Parkway (Bridge No. 2b) located 1,500 feet downstream from this site.
- (6) Arch condition: In upper part, arch is in good shape, but lower part is straight wall.

ggestion: The opening ratio is small. For a very high flood the channel irregularity and the straight part of the opening could be neglected.

gures 9-1-1 to 9-1-5 show the plan view and cross sections at the bridge site. gure 9-1-6 is a topographic map prepared from aerial photographs.





## II. BROOKSIDE PARKWAY, INDIANAPOLIS, CROSSING POGUES RUN

### RESUME

- (1) Compiled number of bridge: No. 2b.
- (2) Location: Lat.  $39^{\circ}47'26''$ , Long.  $86^{\circ}06'41''$ , Indianapolis east, Indiana, quadrangle, sec. 32. T. 16 N., R. 4 E., at bridge on Brookside Parkway, Indianapolis, crossing Pogue Run, eastern central part of Indianapolis.
- (3) Drainage area: 9.2 square miles.
- (4) Tributary to: Tributary to White River, Wabash River basin.
- (5) Slope of channel: 2.9/1000.
- (6) Bridge type: One-span concrete arch bridge.
- (7) Skew toward upstream:  $15^{\circ}$ L.
- (8) Skew toward downstream:  $5^{\circ}$ L.
- (9) Width of bridge: 20 feet.
- (10) Clearance of arch opening: 16 feet.
- (11) Width between banks of channel: 127 feet.
- (12) Eccentricity: No.
- (13) High water mark: 4.8 feet below top of arch, date is uncertain.
- (14) Channel condition:
  - (a) Bend at 170 feet upstream from upstream face of bridge.
  - (b) Bushes distributed along banks both upstream and downstream.
  - (c) Channel bottom is regular but parabolic shape.
  - (d) 18-inch diameter sewer in downstream side.
  - (e) A bridge on North Rial Street, located 2,200 feet downstream from the bridge No. 2b.
- (15) Arch condition: It is a good shape arch.

Suggestion: The channel condition is very good, only one sewer in downstream side. Skew is small. It is recommended to be used for a common flood. However, the influence of  $80^{\circ}$  bend in upstream is uncertain.

Figures 9-2-1 to 9-2-5 show the plan view and cross sections at the bridge site. Aerial photographs of this site are not available.



### III. JEFFERSON AVENUE, INDIANAPOLIS, CROSSING POGUES RUN

#### RESUME

- (1) Compiled number of bridge: No. 2c.
- (2) Location: Lat.  $39^{\circ}47'11''$ , Long.  $86^{\circ}07'28''$ , Indianapolis east, Indiana quadrangle, sec. 31, T. 16 N., R. 4 E., at bridge on Jefferson Avenue, Indianapolis, crossing Pogue Run, eastern central part of Indianapolis.
- (3) Drainage area: 10.3 square miles.
- (4) Tributary to: Tributary to West Fork of White River, Wabash River basin.
- (5) Slope of channel:  $2.4/1000$ .
- (6) Bridge type: One span concrete arch bridge.
- (7) Skew toward upstream:  $5^{\circ}$  R.
- (8) Skew toward downstream:  $5^{\circ}$  L.
- (9) Width of bridge: 45 feet.
- (10) Clearance of arch opening: 11 feet.
- (11) Width between banks of channel: 70 feet.
- (12) Width of channel bottom: 35 feet.
- (13) Eccentricity: None.
- (14) High water mark: Two high water marks, lower one is about 6.7 feet below the top of arch opening, the higher one is about 1.4 feet below top of arch opening. Dates are uncertain.
- (15) Channel condition:
  - (a) No bend close to the bridge site both upstream and downstream side. Channel is straight.
  - (b) Trees and bushes distributed along both side banks of downstream channel.
  - (c) Two sewers upstream side, one 2-foot 6-inch diameter, another one 3-foot 6-inch diameter.
  - (d) Channel bottom is very good, regular and flat.
- (16) Arch condition: Upper part of opening is arch shape, but lower part is straight wall.

Suggestion: The two big sewers are major defect, but the influence is uncertain, otherwise, this is a good site.

Figures 9-3-1 to 9-3-5 show the plan view and crosssections at the bridge site. Figure 9-3-6 is a topographic map of the bridge site prepared from aerial photographs.





#### IV. SOUTH BELMONT AVENUE, INDIANAPOLIS, CROSSING LITTLE BUCK CREEK

##### RESUME

- (1) Compiled number of bridge: No. 8a.
- (2) Location: Lat.  $39^{\circ}40'00''$ , Long.  $86^{\circ}11'47''$ , Maywood, Indiana, quadrangle, on east line sec. 9, T. 14 N., R. 3 E., at bridge on south Belmont Avenue, Indianapolis, crossing Little Buck Creek, southwestern corner of Indianapolis.
- (3) Drainage area: 15.7 square miles.
- (4) Tributary to: Tributary to West Fork White River, Wabash River basin.
- (5) Slope of channel: 1.5/1000.
- (6) Bridge type: One-span concrete arch bridge.
- (7) Skew toward upstream:  $10^{\circ}$  L.
- (8) Skew toward downstream:  $15^{\circ}$  R.
- (9) Width of bridge: 40 feet.
- (10) Clearance of arch opening: 16.5 feet.
- (11) Width between banks of channel: 109 feet.
- (12) Width of channel bottom: Not clear.
- (13) Eccentricity: The low flow part is located in the left side of the channel. The center line of arch is about the same position as the center line between banks.
- (14) High water mark: Flood of 1955, 7.5 feet below top of arch.
- (15) Channel condition:
  - (a) The bridge site is just on a  $25^{\circ}$  curve.
  - (b) The channel is clear.
  - (c) Banks are high enough to confine the flood.
  - (d) Channel bottom is irregular.
  - (e) No sewers nearby.
- (16) Arch condition: It is in good shape but too flat.

Suggestion: The channel is clear and uniform, banks confine the flood flow very well. It is recommended to be used during very high flood, 1 foot or more than the flood of 1955.

Figures 9-4-1 to 9-4-5 show a plan view and cross sections at the bridge site. Figure 9-4-6 is a topographic map of the bridge site prepared from aerial photographs.



# V. STATE ROAD 100, CROSSING WILLIAMS CREEK

## RESUME

- (1) Compiled number of bridge: No. 13.
- (2) Location: Lat.  $39^{\circ}54'44''$ , Long.  $86^{\circ}10'28''$ , Carmel, Indiana, quadrangle, on north line sec. 22, T. 17 N., R. 3 E., at bridge on State Road 100 crossing Williams Creek, 2 1/2 miles northwest of Augusta, Marion County, and 3.8 miles upstream from mouth.
- (3) Drainage area: 17.4 square miles.
- (4) Tributary to: Tributary to West Fork White River, Wabash River basin.
- (5) Slope of channel: about 2/1000.
- (6) Bridge type: One-span concrete arch bridge.
- (7) Skew toward upstream:  $15^{\circ}$  R.
- (8) Skew toward downstream: No skew.
- (9) Width of bridge: 42 feet.
- (10) Clearance of arch opening: 22 feet.
- (11) Width between banks of channel: About 160 feet.
- (12) Width of channel bottom: About 30 feet.
- (13) Eccentricity of arch opening: Center line of arch opening is 10 feet left of the center line of stream.
- (14) High water mark: Flood of April 25, 1961, 14.5 feet below top of arch opening.
- (15) Channel condition:
  - (a) No bend both upstream and downstream within 1,000 feet.
  - (b) Trees and bushes distributed on banks both upstream and downstream.
  - (c) Right banks both upstream and downstream are very low so that the flood water levels were limited to the lower part of arch opening.
  - (d) No sewer nearby.

Suggestion: The arch shape is very good. It is recommended to be used for very high flood.

Figures 9-5-1 to 9-5-5 show a plan view and cross sections at the bridge site. Figure 9-5-6 is a topographic map of the bridge site prepared from aerial photographs.



# VI. VILLA AVENUE, INDIANAPOLIS, CROSSING PLEASANT RUN

## RESUME

- (1) Compiled number of bridge: No. 15a.
- (2) Location: Lat.  $39^{\circ}44'53''$ , Long.  $86^{\circ}07'35''$ , Maywood, Indiana, quadrangle, northeastern corner of sec. 18, T. 15 N., R. 4 E., at bridge on Villa Avenue, Indianapolis, crossing Pleasant Run, south part of Indianapolis.
- (3) Drainage area: 12.9 square miles
- (4) Tributary to: Tributary to West Fork White River, Wabash River basin.
- (5) Slope of Channel: 2.5/1000.
- (6) Bridge type: One span concrete arch bridge.
- (7) Skew toward upstream:  $15^{\circ}$  R.
- (8) Skew toward downstream:  $20^{\circ}$  R.
- (9) Width of bridge: 40 feet.
- (10) Clearance of arch opening: 14.5 feet.
- (11) Width between banks of channel: 116 feet.
- (12) Width of channel bottom: 65 feet.
- (13) Eccentricity of arch opening: Center line of arch opening is at 7 feet right of center line of low flow channel.
- (14) High water mark: Flood of April 1961, 7 feet below top of arch opening.
- (15) Channel condition:
  - (a) Bend at 150 feet downstream from downstream face. Bend at 150 feet upstream from upstream face.
  - (b) Channel is relatively clear and fairly uniform.
  - (c) The banks are high enough to confine the flood water.
  - (d) Bottom is very regular.
  - (e) A fairly large tree near upstream face may obstruct flood flow.
  - (f) Two 1-foot diameter sewers in upstream side.
- (16) Arch condition:
  - (a) Upper part is too flat.
  - (b) Two ends of the arch are elliptic shape.

**Suggestion:** The channel is clear and uniform but the arch seems too flat. It is recommended to be used for segment arch bridge model - prototype comparison. On the other hand, the degree of disturbances due to bends and sewers are uncertain.

Figures 9-6-1 to 9-6-5 show a plan view and cross sections at the bridge site. Figure 9-6-6 is a topographic map of the bridge site prepared from aerial photographs.





# VII. LINDEN AVENUE, INDIANAPOLIS, CROSSING PLEASANT RUN

## RESUME

- (1) Compiled number of bridge: No. 15b.
- (2) Location: Lat.  $39^{\circ}44'45''$ , Long.  $86^{\circ}08'14''$ , Maywood, Indiana quadrangle, west of sec. 18, T. 15 N., R. 4 E., at bridge on Linden Avenue, Indianapolis, crossing Pleasant Run, south part of Indianapolis.
- (3) Drainage area: 13.3 square miles.
- (4) Tributary to: Tributary to West Fork White River, Wabash River basin.
- (5) Slope of channel: 1.5/1000.
- (6) Bridge type: One span concrete arch bridge.
- (7) Skew toward upstream:  $50^{\circ}$  L.
- (8) Skew toward downstream:  $15^{\circ}$  L.
- (9) Width of bridge: 40 feet.
- (10) Clearance of arch opening: 11.5 feet.
- (11) Width between banks of channel: 107 feet.
- (12) Width of channel bottom: 55 feet.
- (13) Eccentricity: None.
- (14) High water mark:
  - (a) Flood of April 1961, 5.8 feet below top of arch.
  - (b) Highest water mark; uncertain date, 1 foot below top of arch.
- (15) Channel condition:
  - (a) Bend at about 200 feet upstream from upstream face.
  - (b) At arch bridge on Shelby Street crossing Pleasant Run at 1000 feet downstream from the bridge.
  - (c) The channel is uniform and clear.
  - (d) The banks are high enough to confine the flood.
  - (e) Channel bottom is very regular.
  - (f) Three 8 inch diameter sewers, one in downstream side and two in upstream side. One 12 inch diameter sewer in right bank of downstream side.
- (16) Arch condition: It seems too flat.

Suggestion: The channel is uniform and clear, but the arch seems too flat. It is recommended to be used for segment arch bridge model - prototype comparison. On the other hand, the degree of disturbances due to upstream bend, downstream bridge and sewers are uncertain.

Figures 9-7-1 to 9-7-5 show a plan view and cross sections at the bridge site. Figure 9-7-6 is a topographic map of the bridge site prepared from aerial photographs.



VIII. STATE ROAD 44 CROSSING HURRICANE CREEKRESUME

- (1) Compiled number of bridge: No. 51
- (2) Location: Lat.  $39^{\circ}28'51''$ , Long.  $86^{\circ}02'53''$ , Franklin, Indiana, quadrangle, sec. 14, T. 12 N., R. 4 E., at bridge on State Road 44, crossing Hurricane Creek, eastern part of Franklin.
- (3) Drainage area: 27 square miles.
- (4) Tributary to: Tributary to Youngs Creek.
- (5) Slope of channel: 1.3/1000.
- (6) Bridge type: Two-span stony arch bridge.
- (7) Skew toward upstream:  $35^{\circ}$  R.
- (8) Skew toward downstream:  $35^{\circ}$  R.
- (9) Width of bridge: 45 feet.
- (10) Clearance of arch opening:
  - 7.5 feet for left side arch.
  - 9 feet for right side arch.
- (11) Width between banks of channel: 43 feet.
- (12) Width of channel bottom: 38 feet.
- (13) Eccentricity: The left part of channel is about 2 feet higher than right side.  
A part of the right side arch is obstructed by the right bank.
- (14) High water mark: 2.4 feet below the top of arches. Date is uncertain.
- (15) Channel condition:
  - (a) The channel is perfectly straight and uniform.
  - (b) Two sewers, one 3.5 feet diameter and one 2 feet diameter are under the right side arch opening.
  - (c) An obstacle, a 2 feet diameter sewer, is at 25 feet downstream from downstream face of bridge.
  - (d) The bank slopes are vertical, both upstream and downstream.
- (16) Arch condition:
  - (a) The shape of the arch is very good.
  - (b) A part of the right side arch is obstructed by the right bank.

Suggestion: The channel is uniform and straight. Since the skew is considerable, it is recommended to be used for skew arch bridge model-prototype comparison. However, the influence of sewers are uncertain.

Figures 9-8-1 to 9-8-5 show a plan view and cross sections at the bridge site.  
Figure 9-8-6 is a topographic map of the bridge site prepared from aerial photographs.







IX. WHITE LICK CREEK NEAR STATE BOYS SCHOOL, PLAINFIELDRESUME

- (1) Compiled number of bridge: No. 59a.
  - (2) Location: Lat. 39°41'35", Long. 86°23'53", Plainfield, Indiana, quadrangle, sec. 35, T. 15 N., R. 1 E., at bridge near State Boys School, Plainfield, crossing White Lick Creek, southern edge of Plainfield.
  - (3) Drainage area: 101 square miles.
  - (4) Tributary to: Tributary to West Fork White River, Wabash River basin.
  - (5) Slope of channel: 1.4/1000.
  - (6) Bridge type: Two-span concrete arch bridge.
  - (7) Skew toward upstream: 5° R.
  - (8) Skew toward downstream: 5° R.
  - (9) Width of bridge: 18 feet.
  - (10) Clearance of arch opening: 16 feet for right side arch, 12 feet for left side arch.
  - (11) Width between banks of channel: 172 feet.
  - (12) Width of channel bottom: Not very clear.
  - (13) Eccentricity: Low flow part of channel is close to right bank.
  - (14) High water mark: Flood of 1957, just about the same height as the top of arch opening.
  - (15) Channel condition:
    - (a) Bend about 250 feet upstream from the bridge.  
Bend about 300 feet downstream from the bridge.
    - (b) Sand heaps distributed along the left part of channel.
    - (c) Left part of channel is 4 feet, average, higher than right side.
    - (d) The banks are able to confine the flood 4 feet lower than the flood of 1957.
  - (16) Arch condition: The arches are in good shape except the ends close to the pier.
- suggestion: This is the best two-span arch bridge under inspection. The defects are the non-symmetric channel cross section and the low bank on left side. So it is recommended to be used for a medium flood.

Figures 9-9-1 to 9-9-5 show a plan view and cross sections at the bridge site.  
Figure 9-9-6 is a topographic map of the bridge site prepared from aerial photographs.



X. DEAN ROAD, INDIANAPOLIS, CROSSING HOWLAND DITCHRESUME

- (1) Compiled number of bridge: No. 66a.
- (2) Location: Lat.  $39^{\circ}53'33''$ , Long.  $86^{\circ}05'54''$ . Fishers, Indiana, quadrangle, sec. 29, T. 17 N., R. 4 E., at bridge on Dean Road, Indianapolis, crossing Howland Ditch, northern part of Indianapolis.
- (3) Drainage area: 4.5 square miles.
- (4) Tributary to: Tributary to West Fork White River.
- (5) Slope of channel: 3.5/1000.
- (6) Bridge type: Original bridge is a one-span concrete arch. Roadway was widened by addition of a one-span concrete flat decked structure on the downstream side of original bridge.
- (7) Skew toward upstream:  $15^{\circ}$  L.
- (8) Skew toward downstream:  $15^{\circ}$  L.
- (9) Width of bridge: Arch part, 18 feet.  
flat part, 13 feet.
- (10) Clearance of arch opening: 7 feet.
- (11) Width between banks of channel: 46 feet.
- (12) Width of channel bottom: 30 feet.
- (13) Eccentricity: None.
- (14) Highwater mark: None.
- (15) Channel conditions:
  - (a) The cross section near the upstream face is larger than cross sections 10 feet upstream.
  - (b) Channel cross sections are regular.
  - (c) Small bend at 120 feet downstream from bridge.
  - (d) Channel is clear.
- (16) Arch condition:
  - (a) Arch opening is in good shape.
  - (b) Flat deck part of this bridge is high enough to be free from disturbing the flow.

Suggestion: Arch is good, channel is clear and regular. Perhaps the drainage area is not big enough to avoid the flash flood.

Figures 9-10-1 to 9-10-5 show a plan view and cross sections at the bridge site. Figure 9-10-6 is a topographic map of the bridge site prepared from aerial photographs.





### II-3 Preliminary Study of the Indirect Determination of Flood Discharge from Contracted Bridge Openings and High Water Marks, by I. P. Wu, Indiana Flood Control and Water Resources Commission

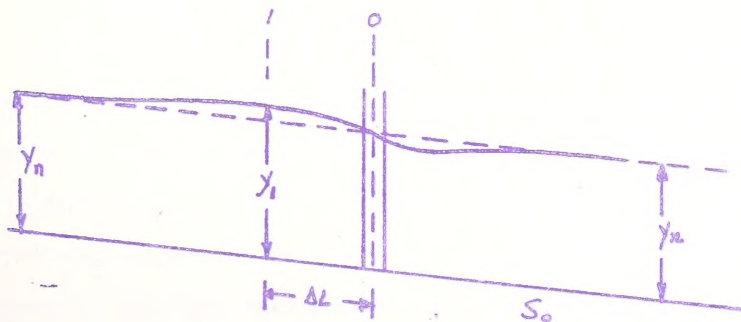
As soon as a bridge is constructed across a natural stream, it serves in at least some degree as a contracted opening to confine the stream flow, particularly in the higher ranges of discharge. Under suitable conditions, such contracted openings provide opportunity for the indirect determination of the flood discharge passing through the bridge opening.

This office has for some years been engaged in a program for the field establishment of high water marks along a number of streams in the State following major floods, including the setting of such marks at and in the vicinity of bridges. The purpose of this study is to develop relationships whereby the high water mark data collected by this office at various bridges may be used to estimate the flood discharge at that point.

The experimental data used herein was obtained from a study by Purdue University on arch bridges and by the University of Colorado on simple normal crossings with a vertical-sided model.

#### Basic Hydraulics and Assumptions for Deriving the Relationship Between the Flood Discharge and High Water Marks

When the flow is contracted by the bridge opening, the flow profile along the center line of the stream can be plotted roughly as follows:







where

section 1 is the section of the highest heading up, the depth is  $y_1$

section o is the section right at the opening, the depth is  $y_o$

$y_n$  = normal depth

$\Delta y$  = the maximum heading up =  $y_1 - y_n$

$v_n$  = normal velocity

$v_1$  = velocity at section 1

$v_o$  = velocity at section o

$S_o$  = channel bottom slope

$L$  = length from the bridge opening to the section of maximum heading up.

By conservation of energy, we have the relation

$$\frac{v_1^2}{2g} + y_1 + S_o \Delta L = \frac{v_o^2}{2g} + y_o + h_f$$

where  $h_f$  is the friction loss from section 1 to section o.

If  $S_o$  is small, so that the term  $S_o \Delta L$  may be neglected, and assuming  $y_o = y_n$ ,

Eq. 1 becomes:

$$\frac{v_1^2}{2g} + y_1 = \frac{v_o^2}{2g} + y_o + h_f$$

$$\frac{v_1^2}{2g} + \Delta y + y_n = \frac{v_o^2}{2g} + y_n + h_f$$

$$\frac{v_1^2}{2g} + \Delta y = \frac{v_o^2}{2g} + h_f$$

Since the high water marks are located on the banks of the stream, the elevation of the marks will be higher than the elevation of the water at the center line of the stream, due to differences in velocity. Assuming that the velocity of flow near the banks is very low or approaching zero, it might be said that  $\Delta y_E$ , which is defined as the difference in elevation between the high water marks on the banks and the depth of normal stream flow  $y_n$ , is  $\Delta y$  plus its velocity head, that is  $\Delta y_E = y + \frac{v_1^2}{2g}$



$$\text{then } \Delta y_E = \frac{v_o^2}{2g} + h_f$$

$$\text{if } h_f = K \frac{v_o^2}{2g}$$

where  $K$  = friction loss coefficient

$$\text{then } \Delta y_E = (1 + K) \frac{v_o^2}{2g}$$

$$\text{or } \frac{\Delta y_E}{y_n} = (1 + K) \frac{v_o^2}{2gy_n}$$

$$\text{and } \frac{\Delta y_E}{y_n} = \frac{1 + K}{2} F_o^2$$

where  $F_o^2$  is the Froude number at the bridge opening.

This gives the relation that  $\Delta y_E$  is a function of the velocity head at the bridge opening and  $\frac{\Delta y_E}{y_n}$  is a function of the Froude number of that opening.

#### Study of Experimental Data

Data from the experimental tests of flow through contracted openings made by the University of Colorado and Purdue University were collected. Since the actual field conditions investigated show that the opening ratio  $M'$  is large and the ratio of  $\Delta y$  and  $y_n$  is small, only those experimental data were selected which met the criteria that  $M' > 0.6$  and  $\frac{\Delta y}{y_n} < 0.1$ . The relations of  $\frac{\Delta y_E}{y_n}$  and  $F_o^2$  can be seen in Figure 11-1, which shows that the data holds the relation:

$$\frac{\Delta y_E}{y_n} = \frac{1}{2} F_o^2$$

$$\text{or } \Delta y_E = \frac{v_o^2}{2g}$$

#### Indirect Determination of Flood Discharge for Indiana Streams

Since the above study shows the relations of high water marks and the velocity at the opening, this will serve as a tool to estimate the peak flood discharge which passed the bridge opening during the particular high water event. Several bridges which are located on a relatively straight and uniform stream, and where the high water mark data is considered to be reliable were selected for this study. There



$$\text{then } \Delta V_E = \frac{V_{02}}{2g} + h_f$$

$$\text{if } h_f = K \frac{V_{02}}{2g}$$

where  $K$  = friction loss coefficient

$$\text{then } \Delta V_E = (1 + K) \frac{V_{02}}{2g}$$

$$\text{or } \frac{\Delta V_E}{V_n} = (1 + K) \frac{V_{02}}{2g V_n}$$

$$\text{and } \frac{\Delta V_E}{V_n} = \frac{1 + K}{2} F_0^2$$

where  $F_0^2$  is the Froude number at the bridge opening.

It gives the relation that  $\Delta V_E$  is a function of the velocity head at the bridge

opening and  $\frac{\Delta V_E}{V_n}$  is a function of the Froude number at that opening.

#### Study of Experimental Data

Data from the experimental tests of flow through contracted openings made by the

University of Colorado and Purdue University were collected. Since the exact critical

depths investigated show that the opening ratio  $W$  is large and the ratio  $W/H$

$W/H$  is small, only those experimental data were selected which met the criteria

$W/H > 0.6$  and  $\frac{\Delta V_E}{V_n} < 0.1$ . The relation of  $\frac{\Delta V_E}{V_n}$  and  $F_0^2$  can be seen in Figure

1, which shows that the data follow the relation:

$$\frac{\Delta V_E}{V_n} = \frac{1}{2} F_0^2$$

$$\text{or } \Delta V_E = \frac{V_n^2}{2}$$

#### Indirect Determination of Flood Discharges for Indian Streams

Since the above study shows the relations of high water marks and the velocity

head, this will serve as a tool to estimate the peak flood discharge which

occurred during the particular high water event. Several bridges

are located on a relatively straight and uniform stream, and where the high

water data is considered to be reliable were selected for this study. These



are also U.S.G.S. gaging stations nearby at which the flood discharge was measured directly.

Information as to high water marks, computed discharge, and the actual discharge for the eight bridges selected for study is as follows:

Bridge Location	Date of Flood	$\Delta y_E$ ft.	Computed Q cfs	Measured Q cfs
Eagle Creek, B&O RR Bridge at Speedway	June 1957	1.37	27,850	25,200
Sugar Creek, at Edinburg	May 1956	0.90	23,000	27,600
Sugar Creek, Hwy. 231 near Crawfordsville	May 1956	0.81	23,700	18,200
Sugar Creek, Hwy. 231 near Crawfordsville	June 1957	1.12	31,400	26,300
Sugar Creek, Hwy. 41 near Byron	May 1956	0.34	19,600	20,600
Raccoon Creek, Hwy. 59 near Mansfield	1957	1.00	37,400	38,400
Flat Rock River, Hwy. 421 near St. Paul	Jan. 1959	0.274	13,300	14,500
Flat Rock River, Hwy. 421 near St. Paul	Nov. 1955	0.265	9,600	10,800

There is shown in Figure 11-2 a plot of  $\Delta y_E$  against the velocity head. Data from the eight bridges shown in the above tabulation, and the experimental study from the University of Colorado and Purdue agree well with the theoretical line  $\Delta y_E = \frac{v_o^2}{2g}$ . It appears that this theoretical line can be used for a rough estimate of the peak flood discharge which passed through the bridge opening.

#### Discussion

Theoretically, the flood discharge passed through the bridge opening is a function of the normal depth of stream flow, the cross section of the channel, the size of the bridge opening, the friction loss in the channel and the bridge opening, and the energy coefficient.

also U.S.D.S. gaging stations nearby at which the flood discharge was measured.

mostly.

Information as to high water marks, computed discharges, and the actual discharge

of the eight bridges selected for study is as follows:

Bridge Location	Date of Flood	Age yr.	Computed discharge	Measured discharge
Big Creek, Big RR Bridge at Spedway	June 1937	1.37	27,830	25,200
Big Creek, at Edinburg	May 1936	0.90	23,000	27,600
Big Creek, Hwy. 231 near Gravellyville	May 1936	0.81	23,700	18,300
Big Creek, Hwy. 231 near Gravellyville	June 1937	1.12	21,400	20,300
Big Creek, Hwy. 41 near Byron	May 1936	0.54	19,600	20,400
Big Creek, Hwy. 39 near Hannibal	1937	1.00	27,200	28,400
Big Creek, Hwy. 121 near St. Paul	June 1939	0.274	13,300	14,500
Big Creek, Hwy. 121 near St. Paul	Nov. 1935	0.263	9,600	10,400

There is shown in Figure 11-2 a plot of  $A \sqrt{g}$  against the velocity head. Data

on the eight bridges shown in the above tabulation, and the experimental study  
University of Colorado and Purdue agree well with the theoretical line  $A \sqrt{g}$ . It  
appears that this theoretical line can be used for a rough estimate of the peak  
flood discharge which passed through the bridge opening.

#### Discussion

Theoretically, the flood discharge passing through the bridge opening is a function  
of the normal depth of stream flow, the cross section of the channel, the size of the  
bridge opening, the friction loss in the channel and the bridge opening, and the

velocity coefficient.

Since the normal depth of the natural channel is difficult to determine, the assumption was made that normal depth occurs at the bridge opening. This was based on the results of the experimental study made by Purdue University, which showed from the flow profiles that normal depth occurred somewhere close to the opening under the condition that the opening ratio  $M^0 > 0.6$  and that the Froude number is smaller than 0.5. The other major assumption was that the velocity of flow close to the bank is very small or approaching zero, such that the elevation of the high water mark on the bank is equal to the elevation of the flow profile along the center line plus its velocity head. Neither of these assumptions can be proved at this time and hence, constitute the weak points of this study.

As the velocities used in this study are all mean velocities, the velocity head actually is not  $\frac{v^2}{2g}$  but  $\alpha \frac{v^2}{2g}$ . The energy coefficient  $\alpha$  is a little larger than one for large uniform channels, but is far greater than one for the section close to a contracted opening. Since it is assumed to be unity in this study, a loss of accuracy undoubtedly results.

As shown in Figure II-1 data from the experimental tests by the University of Colorado and Purdue agree well with the relation  $\frac{\Delta y_E}{y_n} = K F_o^2$ , or  $\Delta y_E = \frac{v_o^2}{2g}$ . This does not mean that the friction coefficient  $K$  is zero, but rather indicates that this factor may be cancelled by the energy coefficient  $\alpha$ , or that there are other undetermined effects as a result of the two basic assumptions.

By studying the relation  $\Delta y_E = \frac{v_o^2}{2g}$ , it will be noted that this is nothing more than the simple statement that the velocity head at the bridge opening is just equal to the maximum heading upstream from the contracted opening. Inasmuch as assumptions made in this study are not quite correct and since the friction loss coefficient  $K$  and energy coefficient  $\alpha$  are not precisely determined, the results of this study can only be used as a rough estimate of the flood discharge or as a check on the flood discharge as determined by other methods.

Further work is necessary to use the experimental data in conjunction with that from actual natural streams to evaluate all the specific factors involved.



Since the normal depth of the natural channel is difficult to determine, the assumption was made that normal depth occurs at the bridge opening. This was based on the results of the experimental study made by Purdue University, which showed that flow profiles that normal depth occurred somewhat closer to the opening under the condition that the opening ratio  $H > 0.6$  and that the Froude number is smaller than 1. The other major assumption was that the velocity of flow close to the bank is very small or approaching zero, such that the elevation of the high water mark on the bank is equal to the elevation of the flow profile along the center line plus the velocity head. Neither of these assumptions can be proved at this time and hence, constitute the weak points of this study.

As the velocities used in this study are all mean velocities, the velocity head usually is not  $\frac{V^2}{2g}$  but  $\frac{V_m^2}{2g}$ . The energy coefficient  $C_E$  is a little larger than 1 for large uniform channels, but is far greater than one for the section close to a contracted opening. Since it is assumed to be unity in this study, a loss of energy undoubtedly results.

As shown in Figure 1, data from the experimental tests by the University of Nevada and Purdue agree well with the relation  $\frac{h}{H} = 0.5 + 0.5 \frac{V^2}{V_0^2}$ . This does not mean that the friction coefficient  $K$  is zero, but rather indicates that  $K$  may be cancelled by the energy coefficient, or that there are other unexplained effects as a result of the two basic assumptions.

By studying the relation  $\frac{h}{H} = \frac{V^2}{V_0^2}$ , it will be noted that this is nothing more than the simple statement that the velocity head at the bridge opening is just equal to the maximum head upstream from the contracted opening. Inasmuch as assumptions in this study are not quite correct and since the friction loss coefficient  $K$  and energy coefficient  $C_E$  are not precisely determined, the results of this study can be used as a rough estimate of the flood discharge or as a check on the flood charges as determined by other methods.

Further work is necessary to use the experimental data in conjunction with that of actual natural streams to evaluate all the specific factors involved.

## APPENDIX A

## NOTATIONS

SYMBOL	DIMENSIONS	DEFINITION
A	$L^2$	Area
$A_1$	$L^2$	Total depth water area at section 1, $A_1 = BY_1$
$A_c$	$L^2$	Critical flow area
$A_{n1}$	$L^2$	Normal depth water area, $A_{n1} = BY_{n1}$
$A_{n2}$	$L^2$	Total depth flow area at section 2
$A_o$	$L^2$	Area of bridge opening
B		Rectangular channel width; Body force per unit of mass
$b^0$	L	Diameter of circle of which the arch segment is a part
b	L	Span width at the springline of the arch
C		A coefficient
C	$L^{1/2}/T$	The Chezy roughness coefficient $= V_n / \sqrt{R_n S}$
$C_1$		Coefficient, see equation 3-7-4
C.V.		Control volume
$C_c$		Coefficient of contraction
C.S.		Control surface
$C_d$		Coefficient of discharge
$C_m$		Correction factor $= M^0/M$ (see Fig. 3-13)
$C_v$		Coefficient of velocity
d	L	Diameter of a circle, distance between center of circular arch segment and channel bottom (Fig. 3-12), depth of flow measured perpendicularly to the bottom.
D	L	Hydraulic depth as defined by $A/W$ ; pipe diameter



## APPENDIX A

## NOTATIONS

SYMBOL	DIMENSIONS	DEFINITION
A	$L^2$	Area
$A_1$	$L^2$	Total depth water area at section 1, $A_1 = B_1^2$
$A_c$	$L^2$	Critical flow area
$A_{c1}$	$L^2$	Normal depth water area, $A_{c1} = B_{c1}^2$
$A_{c2}$	$L^2$	Total depth flow area at section 2
$A_o$	$L^2$	Area of bridge opening
B		Rectangular channel width; Body force per unit mass
$D'$	L	Diameter of circle at which the arch segment is a part
$d$	L	Span width at the springline of the arch
C		A coefficient
$C$	$L^{3/2}T$	The Chezy roughness coefficient $C = \frac{1}{n} \sqrt{g}$
$C_1$		Coefficient, see equation 3-7-4
$C_v$		Control volume
$C_d$		Coefficient of contraction
$C_{d1}$		Coefficient of discharge
$C_d$		Correction factor = $M^2/K$ (see Fig. 3-12)
$C_v$		Coefficient of velocity
$\delta$	L	Diameter of a circle, distance between center of circular arch segment and channel bottom (Fig. 3-12), depth of flow measured perpendicular to the bottom
$D$	L	Hydraulic depth as defined by $A/y$ ; pipe diameter

SYMBOL	DIMENSIONS	DEFINITION
$d'$	L	Distance from the springline to the center of curvature of the arch
$d$	L	Orifice diameter
$E_{1-4}$		Energy loss between section 1 and 4
$e$		Eccentricity
$F$		Denotes a mathematical function, Froude number
$F_f$		Friction force
$F_n$		Normal depth Froude number = $V_n / \sqrt{gY_n}$
$F_s$	F	Surface force on control volume
$f$		Denotes a mathematical function, friction coefficient
$G$		Denotes a mathematical function
$g$		Denotes a mathematical function
$g$	$L/T^2$	Acceleration of gravity
$H$	L	Total energy head
$h_1^*$	L	$I_1 - Y_n$
$h$		Static head
$h_f$	L	Headloss
$K$		Weir coefficient as defined in Francis weir formula
$K$		Head loss due to bridge constriction alone
$k$		Nikuradse's equivalent sand roughness
$L$	L	Length of the bridge in the direction of flow
$L_d$	L	Distance between bridges
$L_{1-3}$	L	Distance between sections 1 and 3



SYMBOL	DIMENSIONS	DEFINITION
$L_{1-4}$	L	Distance between sections 1 and 4
M		Channel width ratio, $b/B$
$M^0$		Channel opening ratio, $A_0/A_n$ for submerged opening; $A_{n2}/A_{n1}$ for unsubmerged opening.
$M_1$		Mild slope backwater curve in an open channel
N		Number of spans
n	$L^{1/6}$	Manning's roughness coefficient
n		Subscript which refers to the normal depth for uniform flow
P	$F/L^2$	Pressure intensity; pier width (See Fig. 3-14)
P	F	Pressure force
$Q_a$	$L^3/T$	Actual discharge through opening
$Q_t$		Theoretical calculated discharge through opening
Q	$L^3/T$	Total flow
q	$L^3/T$	That portion of the total flow which could pass through the bridge without contraction
R	L	Hydraulic radius
$R, R_e$		Reynolds number $V_n R_n / \nu$
r	L	Radius of curvature of the arch, radius of curvature of streamline
S		Slope; head loss per unit length
$S_o$		Slope for normal depth flow in unconfined channel

SYMBOL	DIMENSIONS	DEFINITION
$L_{1-4}$	L	Distance between sections 1 and 4
$M$		Channel width ratio, $b/b$
$M'$		Channel opening ratio, $A_0/A'$ for submerged opening; $A_0/A_1$ for unsubmerged opening
$M_1$		Wald slope backwater curve in an open channel
$N$		Number of spans
$n$	$L^{1/6}$	Manning's roughness coefficient
$\alpha$		Subscript which refers to the normal depth for uniform flow
$P$	$L^{3/2}$	Pressure intensity; plan width (See Fig. 3-11)
$p$	P	Pressure force
$Q_a$	$L^3/T$	Actual discharge through opening
$Q_c$		Theoretical calculated discharge through opening
$Q$	$L^3/T$	Total flow
$q$	$L^3/T$	That portion of the total flow which could pass through the bridge without contraction
$R$	L	Hydraulic radius
$R, R_s$		Hypocycle number $V_{L^2}/V$
$r$	L	Radius of curvature of the arch, radius of curvature of abutments
$s$		Slope; head loss per unit length
$s_0$		Slope for normal depth flow in uncontracted channel



SYMBOL	DIMENSIONS	DEFINITION
T		A series defined in Art. IV-7a
t	T	Time
V	L/T	Average velocity
V <sub>o</sub>	L/T	Average velocity through constriction, Q/A <sub>o</sub>
V <sub>n</sub>	L/T	Average velocity when uniform, normal flow occurs, Q/EY <sub>n</sub>
V		Volt
W	L	Free surface width; weight of water within a control volume
X		Distance along flume
Y	L	Hydraulic depth $\bar{y} = A/W$
Y	L	Depth of flow
Y	L	Head over the center of gravity of a section
Y <sub>1</sub>	L	Depth of flow at section of maximum backwater
Y <sub>c</sub>	L	Critical depth
Y <sub>n</sub> or Y <sub>o</sub>	L	Depth of the normal unconstricted flow
Y <sub>t</sub>	L	Tailgate height
Z		Section factor for critical flow computation $Z^2 = A^3/W$ ; elevation head
$\alpha$		Kinetic energy coefficient
$\alpha'$		Pressure coefficient
$\beta$		Segment factor d/r, Momentum coefficient
$\gamma$	F/L <sup>3</sup>	Specific weight of water
$\delta$		Boundary layer thickness

SYMBOL	DIMENSIONS	DEFINITION
$\delta$		Boundary layer thickness
$\gamma$		Specific weight of water
$\beta$		Segment factor $\beta$ , momentum coefficient
$\alpha'$		Pressure coefficient
$\alpha$		Kinetic energy coefficient
$z$		Section factor for critical flow depth elevation $z = h_c/2$ ; elevation head
$z_c$		Tailgate height
$z_u$ or $z_o$	$L$	Depth of the normal unobstructed flow
$z_o$	$L$	Critical depth
$z_f$	$L$	Depth of flow at section of maximum backwater
$y$	$L$	Head over the center of gravity of a section
$Y$	$L$	Depth of flow
$\bar{Y}$	$L$	Hydraulic depth $\bar{Y} = A/\bar{b}$
$X$		Distance along flume
$W$	$L$	Free surface width; weight of water within a control volume
$v$		Vein
$v_u$	$L/T$	Average velocity when uniform, normal flow occurs, $Q/bL$
$v_o$	$L/T$	Average velocity through constriction, $Q/A_o$
$V$	$L/T$	Average velocity
$t$	$T$	Time
$T$		A series defined in Art. IV-7a

SYMBOL	DIMENSIONS	DEFINITION
$\varepsilon$		Roughness size
$\eta$		$d/r$ (See fig. 3-12)
$\nu$	$L^2/T$	Kinematic viscosity of the fluid
$\rho$	$FT^4/L^4$	Fluid mass density
$\tau$	$F/L^2$	Shear stress
$\phi_1$	degrees	Wingwall angle (See Fig. 3-14)
$\phi_2$	degrees	Skew angle (See Fig. 3-14)
$\theta$	degrees	Angle of inclination of channel



# LIST OF TABLES

Table No.	Description*	Page No.
4-1	Geometries Ib and VII Water Surface Measurements (Small Flume)	176
4-2	Geometry VII Small Flume-Segment Tests-Rough Boundaries	225
5-1	Large Flume Data for Normal Depth Test Runs-Rough Boundaries	227
5-2	Large Flume Tests for the Roughness Parameter $\lambda$	228
7-1-1	Geometry Ia Observed and Calculated Data, Smooth Boundaries	229
7-1-2	Geometry Ia Raw Data-Large Flume-Smooth Boundaries	230
7-1-3	Geometry Ia Calculations for the Large Flume Smooth Boundary Model Tests	234
7-2-1	Geometries Ia and Ib Raw Data-Large Flume-Rough Boundaries	235
7-2-2	Geometries Ia and Ib Calculations for the Large Flume Rough Boundary Model Tests	245
7-2-3	Geometry Ia Surface Topography & Regain Curve Data	248
7-2-4	Geometry Ia Velocity Measurements	251
7-3	Geometry II Raw and Calculated Data	255
7-4	Geometry III Raw and Calculated Data	257
7-5	Geometry IV Raw and Calculated Data	259
7-6	Geometry Va Raw and Calculated Data	262
7-7	Geometry Vb Raw and Calculated Data	264
7-8	Geometry VI Raw and Calculated Data	265
7-9	Geometry VII Raw and Calculated Data	266
8-1	Raw Data-Area of Vena Contracta-Backwater and Profile	267
8-2	Raw Data-Submerged Tests	275
8-3	Raw Data-Submerged Tests	287
8-4	Calculated Values-Run No. 2-140 (Submerged Tests)	289
8-5	Calculated Values-Run No. 141-306 (Submerged Tests)	290

\*Tables 4-1 and 4-2 refer to the small flume preliminary investigations.  
The remaining tables refer to the large flume tests.



# LIST OF TABLES

No.	Description	Page No.
1	Geometries I and VII Water Surface Measurements (Small Plims)	176
2	Geometries VII Small Plims-Depth Test-Depth Boundaries	225
3	Large Plims Data for Small Plims-Depth Test-Depth Boundaries	227
4	Large Plims Tests for the Boundary Parameter $X$	228
5	Geometries Ia Observed and Calculated Data, Smooth Boundaries	229
6	Geometries Ia New Data-Large Plims-Depth Boundaries	230
7	Geometries Ia Calculations for the Large Plims Smooth Boundary Model Tests	234
8	Geometries Ia and Ib New Data-Large Plims-Depth Boundaries	235
9	Geometries Ia and Ib Calculations for the Large Plims Smooth Boundary Model Tests	245
10	Geometries Ia Surface Topography & Depth Data	248
11	Geometries Ia Velocity Measurements	251
12	Geometries II New and Calculated Data	252
13	Geometries III New and Calculated Data	257
14	Geometries IV New and Calculated Data	257
15	Geometries Va New and Calculated Data	262
16	Geometries Vb New and Calculated Data	264
17	Geometries VI New and Calculated Data	265
18	Geometries VII New and Calculated Data	266
19	New Data-Area of Flow Contours-Boundary and Profile	267
20	New Data-Boundary Tests	275
21	New Data-Boundary Tests	287
22	Calculated Values-New No. 2-1A0 (Boundary Tests)	289
23	Calculated Values-New No. 1A1-306 (Boundary Tests)	290

\*Tables 1-1 and 1-2 refer to the small plims preliminary investigations.  
The remaining tables refer to the large plims tests.

TABLE 4-1 WATER SURFACE MEASUREMENTS P.1

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.515	.515	.095	.095	S <sub>0</sub> = 0
4.5							Q <sub>eff</sub> .0114
5.0	9	.420	.515	.515	.095	.095	Dia = 4"
5.5	8.5			.515		.095	Rise = 2"
5.6	8.4			.514		.094	L = 24"
5.7	8.3			.514		.094	
5.8	8.2			.514		.094	
5.9	8.1			.513		.093	Z = 6/8"
6.0	8		.515	.513	.095	.093	Weir Height =
6.1	7.9			.513		.093	
6.2	7.8			.513		.093	h* = .002'
6.3	7.7			.513			Δh = .005'
6.4	7.6			.513		.093	
6.5	7.5			.513			Bridge = 4.035'
6.6	7.4			.513		.093	Position to
6.8	7.2			.512		.092	Along Flume 6.035'
7.0	7	.420	.515	.512	.095	.092	EPB-MFG:
7.065	6.935			.512		.092	.047
7.72	6.28			.513E		.093	
8	6		.515		.095		FIG NO 32
8.24				.514E		.094	
9	5		.515		.095		
9.065	4.035			.515		.095	
9.1	4			.515		.095	
9.3	4.7			.516		.096	
9.5	4.5			.516		.096	
10.0	4	.420	.515	.517	.095	.097	
10.5				.517			
11.0	3		.515	.517	.095	.097	
11.5				.517			
12.0	2		.515	.517	.095	.097	
13.0	1		.515	.517	.095	.097	
14.0	0	.420	.515	.517	.095	.097	



TABLE 4-1 WATER SURFACE MEASUREMENTS P2

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER WITHOUT MODEL	SURFACE MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.425	.538	.538	.113	.113	$S_0 = 0$
4.5	9.5						$Q_{cr} = .0114$
5.0	9		.538	.538	.113	.113	$D_{cr} = 4"$
5.5	8.5						$Rise = 2"$
6.0	8		.538	.538	.113	.113	$L = 24"$
6.5	7.5						$Z = 1"$
7.0	7		.538	.538	.113	.113	$Water$
7.5	6.5				.113		$Height$
7.75	6.25			.538		.113	$h^* = .001$
8.00	6		.538	.537	.113	.112	$\Delta h = .005$
8.1	5.9			.537		.112	$Bridge = 3.5'$
8.2	5.8			.537		.112	$Position$
8.3	5.7			.535		.110	$to$
8.4	5.6			.534		.109	$Along$
8.5	5.5			.535		.110	$Flume$
9.0	5		.538		.113		$5.5'$
9.21				.536E		.111	$EPC-MPG =$
9.5	4.5						.035
9.725				.537E		.112	$FIG NO.$
10.0	4		.538		.113		
10.23				.538E		.113	
10.5	3.5			.538		.113	
10.6	3.4			.539		.114	
10.7	3.3			.539		.114	
10.8	3.2			.539		.114	
10.9	3.1			.539		.114	
11.0	3		.538	.539	.113	.114	
11.5	2.5			.539		.114	
12.0	2		.538	.539	.113	.114	
12.5	2.5						
13.0	1		.538	.539	.113	.114	
13.5	.5						
14.0	0	.425	.538	.539	.113	.114	





TABLE 4-1 WATER SURFACE MEASUREMENTS P.3

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER WITHOUT MODEL	SURFACE MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.515	.515	.095	.095	$S_0 = 0$
4.5	9.5						$Q_{mf} = .0114$
5.0	9		.515	.515	.095	.095	$D_{ia} = 5"$
5.5	8.5			.514		.094	$Rise = 2.5"$
5.9	8.1			.514		.094	$L = 24"$
6.0	8	.420	.515	.513	.095	.093	$Z = 6/8"$
6.1	7.9			.513		.093	Weir =
6.2	7.8			.513		.093	Height =
6.3	7.7			.513		.093	$h^* = .001$
6.4	7.6			.513		.093	$\Delta h = .003$
6.5	7.5			.513		.093	Bridge = 5'
6.6	7.4			.513		.093	Position to
6.7	7.3			.513		.093	Along
6.8	7.2			.513		.093	Flume
6.9	7.1		.515	.513	.095	.093	EPG-MPG =
7.0	7			.514E		.094	.047
7.24	6.76						FIG. NO. 31
8.0	6	.420	.515		.095		
8.24				.515E		.095	
9.0	5		.515	.516	.095	.096	
9.1	4.9			.516		.096	
9.2	4.8			.516		.096	
9.3	4.7			.516		.096	
9.4	4.6			.516		.096	
9.5	4.5			.516		.096	
10.0	4	.420	.515	.516	.095	.096	
10.5				.516		.096	
11.0	3		.515	.516	.095	.096	
11.5							
12.0	2		.515	.516	.095	.096	
12.5							
13.0	1		.515	.516	.095	.096	
13.5							
14.0	0	.420	.515	.516	.095	.096	



## TABLE 2-1 WATER SURFACE MEASUREMENTS P.4

STATION	DISTANCE ALONG FLUME	POINT GAGE BEARING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.425	.538	.538	.113	.113	Set 0
4.5	9.5						with .0114
5.0	9		.537	.538	.113	.113	Disc 5"
5.5	8.5					.113	Rise 2.5"
6.0	8		.538	.538	.113	.113	Disc 24"
6.5	7.5						
7.0	7.0		.538	.538	.113	.113	
7.5	6.5						Disc 1"
8.0	6.0		.538	.538	.113	.113	Water Height =
8.1	5.9			.537		.112	Disc =
8.2	5.8			.536		.111	Disc = .001
8.3	5.7			.535		.110	Disc = .005
8.4	5.6			.534		.109	
8.5	5.5			.534		.109	Disc 3.5'
8.695	5.315			.533E		.108	Position to
9.0	5.0		.538		.113		Disc 5.5'
9.19				.534E		.109	
9.5	4.5						Disc =
9.693				.535E		.110	Disc = .035
10.0	4.0		.538		.113		
10.183				.536E		.111	
10.5	3.5		.538	.537	.113	.112	
10.6	3.4			.537		.112	
10.7	3.3			.538		.113	
10.8	3.2			.539		.114	
10.9	3.1			.539			
11.0	3.0		.538	.539	.113	.114	
11.5	2.5			.539			
12.0	2.0		.538	.539	.113	.114	
12.5	1.5			.539			
13.0	1.0		.538	.539	.113	.114	
13.5	.5						
14.0	0	.425	.538	.539	.113	.114	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 5

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOT TOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.515	.515	.095	.095	So= 0
4.5	9.5						Q <sub>m</sub> .0114
5.0	9	.420	.515	.515	.095	.095	Dia= 7.7"
5.5	8.5						Rise= 1.4"
6.0	8	.420	.515	.515	.095	.095	L= 9.7"
6.5	7.5						
7.0	7		.515	.515	.095	.095	Z= 6/8"
7.5	6.5						Weir Height =
7.7	6.3		.515	.515		.095	
7.8	6.2			.514		.094	
7.9	6.1			.514		.094	h* = .001
8.0	6	.420	.515	.514	.095	.094	Δh = .003
8.1	5.9			.514		.094	
8.2	5.8			.514		.094	Bridge = 4.45'
8.5	5.5			.514		.094	Position to
8.75	5.25			.513		.093	Along to
9.0	5						Flume 5.25'
9.55	4.45			.515	.095	.095	EPG - M PG =
9.60	4.4		.515	.516	.095	.096	
9.7	4.3			.516		.096	FIG NO <del>30</del>
9.8	4.2		.515	.516	.095	.096	
9.90	4.1			.516		.096	
10.0	4	.420	.515	.516	.095	.096	
10.5							
11.0	3		.515	.516	.095	.096	
11.5							
12.0	2	.420	.515	.516	.095	.096	
12.5							
13.0	1		.515	.516	.095	.096	
13.5							
14.0	0	.420	.515	.516	.095	.096	





TABLE 4-1 WATER SURFACE MEASUREMENTS P 6

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.520	.520	.10	.10	$S_o = 0$
5.0	9		.520	.520	.10	.10	$Q_{mf} = .0138$
5.5	8.5						Dia = 4"
6.0	8	.420	.520	.520	.10	.10	Rise = 2"
7.0	7		.520	.520	.10	.10	L = 24"
7.5	6.5			.520	.10	.10	
7.6	6.4			.519		.099	Z = 6/8"
7.7	6.3			.518		.098	Weir
7.8	6.2			.518		.098	Height =
7.9	6.1			.518		.098	$h^* =$
8.0	6	.420	.520	.518	.10	.098	$h^* = .001'$
8.1	5.9			.518		.098	$\Delta h = .004'$
8.2	5.8			.518		.098	Bridge = 3'
8.3	5.7			.518		.098	Position to
8.4	5.6			.518		.098	Along
8.5	5.5			.517		.097	Flume 5'
8.6	5.4			.517		.097	EPG-M.P.G. =
8.7	5.3			.517		.097	.047
8.8	5.2			.517		.097	FIG. NO.
8.9	5.1			.517		.097	
9.0	5		.520	.517	.10	.097	
9.71	4.29			.518E		.098	
10	4	.420	.520		.10		
10.22	3.78			.519E		.099	
11.0	3		.520	.520	.10	.10	
11.1	2.9			.521		.11	
11.3	2.7			.522		.12	
11.5	2.5			.522		.12	
12.0	2		.520	.522	.10	.12	
13.0	1		.520	.522	.10	.12	
14.0	0	.420	.520	.522	.10	.12	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 7

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.520	.520	.100	.10	$S_o = 0$
4.5							$Q_{mf} = .0138$
5.0	9	.420	.520	.520	.10	.10	Dia = 5"
5.5							Rise = 2.5"
6.0	8	.420	.520	.520	.10	.10	L = 24"
6.5							
7.0	7		.520	.520	.10	.10	Z = 6/8"
7.3	6.7			.519		.099	Weir =
7.4	6.6			.519		.099	Height =
7.5	6.5			.519		.099	
7.6	6.4			.519		.099	$h^* = .001'$
7.7	6.3			.519		.099	$\Delta h = .003'$
7.8	6.2			.519		.099	
8.0	6	.420	.520	.519	.10	.099	Bridge = 3'
8.2	5.8						Position to
8.4	5.6			.519		.099	Along
8.5	5.5			.518		.098	Flume 5'
8.7	5.3			.518		.098	EPG-M.P.G =
9.0	5			.518		.098	.047
9.23	4.67			.519E		.099	FIG. NO.
10.0	4						
10.23	3.67			.519E		.099	
11.0	3	.420	.520	.520	.10	.10	
11.1	2.9			.520		.10	
11.2	2.8			.521		.101	
11.3	2.7			.521		.101	
11.4	2.6			.521		.101	
11.5	2.5			.521		.101	
11.75	2.25			.521		.101	
12.0	2	.420	.520	.521	.10	.101	
12.5				.521		.101	
13.0	1			.521		.101	
13.5				.521		.101	
14.0	0	.420	.520	.521	.10	.101	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 8

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.520		.10	.10	So= 0
5.0	9		.520		.10	.10	Q <sub>mf</sub> = .0138
6.0	8		.520		.10		Dia= 7.7"
7.0	7.0		.520	.520	.10	.10	Rise= 1.4"
7.25	6.75			.520			L= 9.7"
7.7	6.3						
7.9	6.1		.520	.520	.10	.10	Z= 6/8"
8.0	6.0	.420	.520	.519	.10	.099	Weir Height =
8.3	5.7			.518		.098	
8.5	5.5			.518		.098	h* = .001'
8.75	5.25			.518		.098	Δh = .003'
9.0	5.0		.520		.10		
9.50							
9.55	4.45			.519		.099	Bridge = 4.45'
9.60	4.4			.520		.100	Position to
9.70	4.3			.520		.100	Along
9.8	4.2			.520		.100	Flume 5.25'
10.0	4.0	.420	.520	.520	.10	.100	EPG-M.P.G=
10.25	3.75			.521		.101	
10.50	3.5			.521		.101	FIG. NO. <del>93</del>
11.0	3.0		.520	.521	.10	.101	
11.5	2.5			.521		.101	
11.75	2.25			.521		.101	
12.0	2.0			.521	.10	.101	
13.0	1.0		.520	.521	.10	.101	
14.0	0	.420	.520	.521	.10	.101	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 9

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.425	.542	.542	.117	.117	S <sub>0</sub> = 0
4.1	9.9			.541		.116	Q <sub>mf</sub> .0138
4.2	9.8			.540		.115	Dia= 7.7"
4.3	9.7			.539		.114	Rise=1.4"
4.4	9.6			.538		.113	L= 9.7"
4.5	9.5			.537		.112	
4.655	9.345			.539E		.114	
5.0	9		.542		.117		Z= 1"
5.14	8.86			.540E		.115	Weir Height =
5.3	8.7			.541		.116	
5.4	8.6			.541		.116	h*= .001
5.5	8.5			.542		.117	Δh= .006
5.6	8.4			.542		.117	
6.0	8.0	.425	.542	.543	.117	.118	Bridge = 8.7'
6.5	7.5			.543		.118	Position to
7.0	7			.543		.118	Along Flume 9.5'
7.5	6.5			.543		.118	
8.0	6	.425					EPG-MPG=
8.5	5.5			.543	.117	.118	.042
9.0	5						FIG NO. <del>29</del>
9.5	4.5			.543		.118	
10.0	4	.425	.542		.117		
10.5	3.5			.543	.117	.118	
11.0	3						
11.5	2.5			.543		.118	
13.0	1			.543		.118	
13.5							
14.0	0	.425	.542	.543	.117	.118	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 12

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4	10	.425	.542	.542	.117	.117	$S_o = 0$
4.5							$Q_{mf} = .0139$
5.0	9		.542	.542	.117	.117	$D_{ia} = 4"$
5.5							$Rise = 2"$
6.0	8	.425	.542	.542	.117	.117	$L = 24"$
6.5	7.5						
7.0	7.0		.542	.542			$Z = 1"$
7.4	6.6		.542	.542	.117	.117	Weir
7.5	6.5			.541		.116	Height =
7.6	6.4			.540		.115	
7.7	6.3			.539		.114	$h^* = .001$
7.8	6.2			.539		.113	$\Delta h = .005$
7.9	6.1			.537		.112	
8.0	6.0	.425	.542	.538	.117	.113	Bridge = 4'
8.70	5.30			.537E			Position to
9.0	5.0		.542	.538E	.117		Along
9.72				.541E			Flume 6'
10.0	4.0	.425	.542	.542	.117	.117	EPG-MPG =
10.1	3.9			.543		.118	.035
10.2	3.8			.543		.118	FIG. NO. <del>20</del>
10.3	3.7			.543		.118	
10.4	3.6			.543		.118	
10.5	3.5			.543			
11.0	3.0		.542	.543	.117	.118	
11.5				.543			
12.0	2.0	.425	.542	.543	.117	.118	
12.5				.543		.118	
13.0	1.0		.542	.543	.117	.118	
13.5				.543		.118	
14.0	0	.425	.542	.543	.117	.118	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 13

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4	10	.425	.542	.542	.117	.117	$S_o = 0$
4.5							$Q_m = .0139$
5.0	9	.425		.542	.117	.117	Dia = 5"
5.5							Rise = $2\frac{1}{2}$ "
6.0	8	.425	.542	.542	.117	.117	L = 24"
6.5							
7.0	7	.425	.542	.542	.117	.117	Z = 1"
7.5	6.5		.542	.542	.117	.117	Weir =
7.6	6.4			.540		.115	Height =
7.7	6.3			.539		.114	
7.8	6.2			.539		.114	$h^* = .001$
7.9	6.1			.539		.114	$\Delta h = .004$
8.0	6.0	.425		.539		.114	
8.19				.540E			Bridge = 4'
8.5	5.5		.542		.117		Position to
8.69				.541E			Along
9.0	5	.425					Flume 6'
9.185				.541E			EPG-M.P.G. =
9.69				.541E			.035
10	4	.425	.542		.117		FIG. NO. <del>19</del>
10.1	3.9		.542	.542	.117	.117	
10.2	3.8			.543		.118	
10.3	3.7			.543		.118	
10.4	3.6			.543		.118	
10.5	3.5			.543		.118	
11.0	3	.425	.542	.543	.117	.118	
11.5				.543		.118	
12.0	2	.425	.542	.543	.117	.118	
12.5				.543		.118	
13.0	1	.425	.542	.543	.117	.118	
13.5				.543		.118	
14.0			.542	.543	.117	.118	
14.5	0	.425	.542	.543	.117	.118	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 14

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10.0	.423	.541	.541	.118	.118	Sgt 0
5.0	9.0			.541		.118	Onp .015
5.5	8.5			.541		.118	Dip = 4"
5.75	8.25			.540		.117	Rise = 2"
6.0	8.0	.423	.541	.540	.118	.117	L = 24"
6.5	7.3			.539		.116	
6.8	7.2			.538		.115	L = 1"
7.0	7.0			.538		.115	Weir height =
7.72	6.28			.539E		.116	
8.0	6.0	.423	.541		.118		h* = .002'
8.24	5.76			.540E		.117	Δh = .005'
9.0	5	.423	.541	.541	.118	.118	
9.1	4.9			.542		.119	Bridge = 5'
9.3	4.7			.543		.120	Position to
9.5	4.5			.543		.120	Along to
10.0	4	.423	.541	.543	.118	.120	Flume 7'
11.0	3	.423	.541	.543	.118	.120	EPG-MPG =
11.5	2.5			.543	.118	.120	.047
12.0	2	.423	.541	.543	.118	.120	
13.0	1	.423	.541	.543	.118	.120	FIG NO
14.0	0	.423	.541	.543	.118	.120	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 15

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4	10.0	.423	.541	.541	.118	.118	So= 0
5	9.0	.423	.541	.541	.118	.118	Q <sub>mf</sub> .015
5.5	8.5						Dia= 5"
5.7	8.3			.541		.118	Rise= 2.5"
5.8	8.2			.540		.117	L= 24"
6.0	8.0	.423	.541	.540	.118	.117	
6.2	7.8			.539		.116	Z= 1"
6.5	7.5			.539		.116	Weir Height =
6.8	7.2			.539		.116	
7.0	7.0	.423	.541	.539	.118	.116	h* = .001'
7.24	6.76			.540E		.117	Δh = .003'
7.75	6.25			.540E		.117	
8.24	5.76			.541E		.118	Bridge = 5'
8.75	5.25			.541E		.118	Position to
9.0	5	.423	.541	.542	.118	.119	Along Flume 7'
9.2	4.8			.542		.119	
9.5	4.5			.542		.119	EPG-MPG=
9.75	4.25			.542		.119	.047
10.0	4	.423	.541	.542	.118	.119	FIG NO
10.5	3.5			.542			
11.0	3			.542		.119	
12.0	2	.423	.541	.542	.118	.119	
13.0	1			.542		.119	
14	0	.423	.541	.542	.118	.119	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 16

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4	10.0	.423	.541	.541	.118	.118	$S_0 = 0$
6.0	8.0	.423	.541	.541	.118	.118	$Q_m = .015$
6.5	7.5			.540		.117	$D_{10} = 7.7"$
6.75	7.25			.540		.117	Rise = 1.4"
7.0	7	.423	.541	.540	.118	.117	L = 9.7"
7.25	6.75			.540		.117	
7.5	6.5			.539		.116	
7.8	6.2			.539		.116	Z = 1"
8.0	6	.423	.541	.539	.118	.116	Weir =
8.8	5.2			.543		.120	Height =
9.0	5	.423	.541	.543	.118	.120	$h^* = .002'$
9.3	4.7			.543		.120	$\Delta h = .004'$
9.5	4.5			.543		.120	
10.0	4	.423	.541	.543	.118	.120	Bridge = 5.2'
11.0	3			.543		.120	Position to
12.0	2	.423	.541	.543	.118	.120	Along Flume 6.0'
12.5	1.5						
13.0	1	.423	.541	.543	.118	.120	EPG-MFG
14.0	0	.423	.541	.543	.118	.120	.047
							FIG NO



## ALL 2-1 WATER SURFACE MEASUREMENTS P. 17

STATION	DISTANCE ALONG FLUME	DEPTH GAGE READINGS			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOT TOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.421	.495	.495	.074	.074	S <sub>0</sub> = 0
5.0	9	.421	.495	.495	.074	.074	Q <sub>17</sub> .017
6.0	8	.421	.495	.495	.074	.074	Dip = 7.7"
7.0	7	.421	.495	.495	.074	.074	Rise = 1.4"
8.0	6	.421	.495	.495	.074	.074	L = 9.7"
9.0	5	.421	.495	.495	.074	.074	
10.0	4		.495	.495	.074	.074	
10.10	3.9			.494		.073	Z = 3/8"
10.2	3.8			.494		.073	Ver
10.3	3.7			.493		.072	Height =
10.4	3.6			.493		.072	n <sup>2</sup> = .001'
10.5	3.5			.492		.071	dh = .004'
10.685	3.315			.492		.071	
11.0	3	.421	.495		.074		Bridge = 2.65'
11.485	2.515						Position to
11.57	2.43			.494		.073	Along
11.6	2.4			.495		.074	Flume 3.25'
11.65	2.35			.495		.074	EDM = 4.43 =
12.0	2	.421	.495	.496	.074	.075	
12.5	1.5			.496		.075	FIG. NO. <del>34</del>
13.0	1	.421	.495	.496	.074	.075	
13.5	.5			.496		.075	
14.0	0	.421	.495	.496	.074	.075	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 18

191

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.421	.512	.512	.091	.091	So= 0
5.0	9		.512	.512	.091	.091	Q <sub>mf</sub> .028
6.0	8		.512	.512	.091	.091	Dia= 7.7"
7.0	7		.512	.512	.091	.091	Rise= 1.4"
8.0	6		.512	.512	.091	.091	L= 9.7"
9.0	5		.512	.512	.091	.091	
10.0	4		.512	.512		.091	Z= 3/8"
10.1	3.9		.512	.511		.090	Weir
10.2	3.8			.510		.089	Height =
10.3	3.7			.509		.088	
10.6	3.4			.508		.087	h* = .005'
10.77	3.23						Δh = .009'
11.0	3		.512		.091		Bridge = 2.45'
11.55	2.45						Position to
11.7	2.3			.514		.093	Along
11.8	2.2			.515		.094	Flume 3.23'
11.9	2.1			.516		.095	EPG-MPG =
12.0	2		.512	.517	.091	.096	
12.5				.517		.096	
13.0	1		.512	.517	.091	.096	FIG NO. <del>35</del>
13.5				.517		.096	
14.0	0	.421	.512	.517	.091	.096	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 19

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.423	.571	.571	.148	.148	$S_o = 0$
5.0	9		.571	.571	.148	.148	$Q_m = .031$
6.0	8		.571		.148		$Dia = 4"$
6.5	7.5		.571		.148		$Rise = 2"$
7.0	7		.571	.571	.148	.148	$L = 24"$
7.1	6.9			.570		.147	
7.3	6.7			.569		.146	
7.5	6.5			.568		.145	$Z = 6/8"$
7.8	6.2			.568		.145	Weir Height =
8.0	6			.567		.144	
8.2	5.8			.565		.142	$h^* = .005'$
8.3	5.7			.565		.142	$\Delta h = .011'$
8.6	5.4			.565		.142	
8.7	5.3			.565		.142	Bridge = 3'
8.9	5.1			.565		.142	Position to
9.0	5			.565	.148	.142	Along Flume 5'
10.0	4		.571		.148		EPG-MPG=
11.0	3			.572	.148	.149	
11.1	2.9			.573		.150	
11.2	2.8			.574		.151	FIG. NO. <del>37</del>
11.3	2.7			.575		.152	
11.4	2.6			.576		.153	
12.0	2			.576		.153	
12.5	1.5			.576		.153	
13.0	1			.576		.153	
13.5				.576		.153	
14.0	0	.423	.571	.576	.148	.153	





TABLE 4-1 WATER SURFACE MEASUREMENTS 20

TABLE 7. WATER SURFACE MEASUREMENTS 20							
STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.421	.611	.611	.190	.190	$S_o = 0$
5.0	9	.421	.611	.611	.190	.190	$Q_m = .0519$
6.0	8						$Dia = 5"$
7.0	7.0			.611		.190	$Rise = 2.5"$
8.0	6.0	.421	.611	.611	.190	.190	$L = 24"$
8.8	5.2		.611	.611	.190	.190	
9.0	5.0			.611	.190	.190	$Z = 6/8"$
9.1	4.9			.610		.189	Weir
9.3	4.7			.609		.188	Height =
9.5	4.5			.607		.187	
9.532	4.468			.606		.186	$h^* = .006'$
10.0	4.0	.421	.611		.190		$\Delta h = .011'$
10.5	3.5						
11.0	3.0						Bridge = 2.468'
11.5	2.5						Position to
11.532	2.468			.612		.191	Along
11.6	2.4			.615		.194	Flume 4.468'
11.7	2.3			.616		.195	EPG-MPG
12.0	2.0	.421	.611	.617	.190	.196	
12.5	1.5			.617		.196	FIG NO. <del>36</del>
13.0	1.0			.617		.196	
13.5	.5			.617		.196	
14.0	0	.421	.611	.617	.190	.196	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 21

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.422	.531	.531	.109	.109	$S_o = .0003$
4.5	9.5						$Q_{mf} = .0113$
5.0	9	.422	.531	.531	.109	.109	$D_{ie} = 4"$
5.5	8.5						$Rise = 2"$
6.0	8	.423	.532	.532	.109	.109	$L = 24"$
6.5	7.5						
7.0	7	.423	.532	.532	.109	.109	$Z = 1"$
7.1	6.9			.531		.108	Weir
7.2	6.8			.531		.108	Height
7.3	6.7			.531		.108	
7.4	6.6			.531		.108	$h^* = .002$
7.5	6.5			.530	.109	.107	$\Delta h = .005$
7.93	6.02			.530E			
8.19	5.81			.530E			Bridge = 4.5'
8.70	5.30			.531E			Position to
9.20	4.80			.532E			Along Flume 6.5'
9.5	4.5		.532	.534		.112	FIG. NO. 22
9.6	4.4			.534			
9.7	4.3			.535			.042
9.8	4.2			.535			
9.9	4.1			.53		.112	
10.0	4	.424	.533	.535	.109	.112	
10.5	3.5			.535			
11.0	3			.535			
11.5				.535			
12.0	2			.535			
12.5		.425	.534	.534	.109	.109	
13.0	1						
13.5							
14.0	0	.425	.534	.534	.109	.109	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 22

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.422	.538	.538	.116	.116	$S_0 = .0003$
4.1	9.9			.537		.115	$Q_m = .0138$
4.2	9.8			.537	.116	.115	$D_{90} = 7.7"$
4.3	9.7			.536		.114	$Rise = 1.4"$
4.4	9.6			.535		.113	$L = 9.7"$
4.5	9.5			.535	.116	.113	
4.68	9.32			.536E		.114	$Z = 1"$
4.93				.537E		.115	Weir Height =
5.0	9						
5.3	8.7			.539		.117	
5.4	8.6			.539		.117	$h^* = .001$
5.5	8.5			.539		.117	$\Delta h = .004$
5.6	8.4			.539		.117	
5.7	8.3						Bridge = 8.7'
5.8	8.2						Position to
5.9	8.1						Along
6.0	8						Flume 9.5'
6.5	7.5	.423		.540		.117	EPR - 14.3 =
7.0	7	.423	.539	.540	.116	.117	.042
7.5	6.5						FIG NO. <del>28</del>
8.0	6			.540		.117	
8.5	5.5			.541		.117	
9.0	5			.541		.117	
9.5	4.5			.541		.117	
10.5	3.5			.541		.117	
11.0	3	.424	.540	.541	.116	.117	
12.0	2			.541		.117	
12.5	1.5						
13.0	1	.425		.542		.117	
14.0	0	.425	.541	.542	.116	.117	





TABLE 4-1 WATER SURFACE MEASUREMENTS P.23

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4	10	.420	.531	.531	.111	.111	$S_0 = .0003$
4.5	9.5			.531		.111	$Q_{mf} = .0114$
4.6	9.4			.530	.111	.110	$D_{10} = 4"$
4.7	9.3			.530		.110	$Rise = 2"$
4.8	9.2			.529		.109	$L = 24"$
4.9	9.1			.529		.109	
5.0	9	.420	.531	.529	.111	.109	$Z = 1"$
5.76	8.24			.530E		.110	Weir Height =
6.0	8		.531		.111		
6.28	7.78			.530E		.110	$h^* = .001'$
6.78	7.22			.530E		.110	$\Delta h = .003'$
7.0	7		.531	.531	.111	.110	
7.1	6.9			.531		.111	Bridge = 7'
7.2	6.8			.531		.111	Position to
7.3	6.7			.532		.112	Along
7.4	6.6			.532		.112	Flume 9'
7.5	6.5	.421	.532	.533	.111	.112	EPG-MPG =
7.6	6.4			.533		.112	.045
7.7	6.3			.533		.112	FIG. NO.
7.8	6.2			.533		.112	
7.9	6.1			.533		.112	
8.0	6		.532	.533	.111	.112	
9.0	5		.532	.532	.111	.111	
10.0	4		.532	.532	.111	.111	
11.0	3	.422	.533	.533	.111	.111	
12.0	2		.533	.533	.111	.111	
13.0	1		.533	.533	.111	.111	
14.0	0	.423	.534	.534	.111	.111	









## 2-1 WATER SURFACE MEASUREMENTS P.25

STATION	DISTANCE ALONG FLOVE	POINT GAUGE READINGS			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	WATER SURFACE MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.422	.532	.532	.110	.110	SLT .0003
4.1	9.9			.531		.109	Gage .0114
4.2	9.8			.531		.109	Gage 7.7 "
4.3	9.7			.531		.109	Gage 1.4"
4.4	9.6			.531	.110	.109	Gage 9.7"
4.5	9.5			.529		.107	
4.68	9.32			.530E		.108	
4.93				.532E		.110	1"
5.0	9	.422	.532		.110		
5.3	8.7			.532		.110	
5.4	8.6			.533	.110	.111	.001
5.5	8.5			.534		.111	.005
5.6	8.4			.534		.111	
5.8	8.2				.110		8.7'
5.9	8.1						to
6.0	8.0	.423		.534		.111	9.5'
6.5	7.5			.534			
7.0	7.0	.423	.533	.534	.110	.111	.042
7.5	6.5			.534		.111	
8.0	6.0			.534		.111	
8.5	5.5			.534		.111	
9.0	5.0			.534	.110	.111	
9.5	4.5			.534			
10.5				.535			
11.0	3.0	.424	.534	.535	.110	.111	
12.0	2.0			.535		.111	
13.0	1.0		.535	.535	.110	.110	
14.0	0	.425	.535	.535	.110	.110	



TABLE 4-1 WATER SURFACE MEASUREMENTS P.26

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOT TOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4	10	.420	.531	.531	.111	.111	So= .0003
4.1	9.9			.531	.111	.111	Q <sub>m</sub> = .0114
4.2	9.8			.531	.111	.111	Dia= 7.7"
4.3	9.7			.530	.111	.110	Rise= 1.4"
4.4	9.6			.530		.110	L= 9.7"
4.5	9.5			.530		.110	
5.0	9		.531		.111		Z= 1"
5.3	8.7		.531	.531	.111	.111	Weir =
5.4	8.6			.531	.111	.111	Height =
5.5	8.5			.532	.111	.112	h* = .001'
5.6	8.4			.532	.111	.112	Δh = .002'
5.7	8.3			.532	.111	.112	
5.8	8.2			.532	.111	.112	Bridge = 8.7'
6.0	8			.532	.111	.112	Position to
6.5	7.5			.532	.111	.112	Along
7.0	7			.532	.111	.112	Flume 9.5'
7.5		.420	.531	.532	.111	.112	EPG-MRG=
8.0	6	.421	.532	.532	.111	.111	.045
9.0	5			.532	.111	.111	FIG. NO.
10.0	4			.532			
11.0	3	.422	.533	.533	.111	.111	
12.0	2			.533	.111	.111	
13.0	1			.533			
14.0	0	.423	.534	.534	.111	.111	



TAP F 4-1 WATER SURFACE MEASUREMENTS P. 27

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	MODEL IN PLACE			
	2	3	4	5	6	7	8
4.0	10	.422	.534	.534	.112	.112	Set .0003
4.5	9.5						Q <sub>gt</sub> .0115
5.0	9		.534	.534	.112	.112	Dir = 5"
5.5	8.5						Rise = 2.5"
6.0	8						24"
6.7			.534	.534	.112	.112	
6.8	7.2		.534	.534	.112	.112	
6.9	7.1	.423	.534	.534			Z = 1"
7.0	7	.423	.535	.534	.112	.111	Water Height
7.1	6.9			.534		.111	
7.2	6.8			.533	.112	.110	K <sub>z</sub> .001
7.3	6.7			.533	.112	.110	Δn = .006
7.4	6.6			.533	.112	.110	
7.5	6.5	.423	.535	.531	.112	.108	Bridge = 4.5'
7.12	6.12			.531E		.108	Position to
8.13	5.87			.530E		.107	Flume 6.5'
8.50	5.5						EPB-MB3-
8.63				.532E		.109	.042
9.0				.534E		.111	
9.5	4.5	.423	.535	.536	.112	.113	<del>Q<sub>gt</sub> .0115</del>
9.6	4.4			.537	.112	.113	
9.7	4.3			.537			
9.8	4.2			.537	.112	.113	
9.9	4.1			.537			
10.0	4	.424	.536	.537	.112	.113	
10.5	3.5			.537			
11.0	3	.425	.537	.537	.112	.112	
11.5	2.5			.537			
12.0	2			.537			
12.5	1.5			.537	.112	.112	
13.0	1		.537	.537			
14.0	0	.425	.537	.537	.112	.112	





TABLE 2-1 WATER SURFACE MEASUREMENTS P.28

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER WITHOUT MODEL	SURFACE MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.422	.541	.541	.119	.119	S <sub>0</sub> = .0003
4.5	9.5		.541	.541	.119	.119	C <sub>m</sub> = .015
5.0	9		.541	.541		.119	Dia = 6"
5.5	8.5		.541	.541		.119	Rise = 2"
5.6	8.4		.541	.540		.118	L = 24"
5.7	8.3			.540		.118	Z = 1"
5.8	8.2			.540		.118	Water Height =
5.9	8.1			.540		.118	
6.0	8			.540		.118	
6.1	7.9			.539		.117	
6.2	7.8			.538		.116	h* = .002
6.3	7.7			.538		.116	Δh = .008
6.4	7.6			.537		.116	
6.5	7.5	.423	.542	.536	.119	.116	Bridge Elevation to Along Flume = 5.5'
7.0	7						7.5'
7.22	6.78			.536E			
7.5							EPG-A-EG-
7.735	6.265			.537E			.042
8.0	6			.539E			EG No 26 =
8.5	5.5			.541		.118	
8.6	5.4			.542		.119	
8.7	5.3			.543		.120	
8.8	5.2			.543		.120	
8.9	5.1			.543		.120	
9.0	5			.544		.120	
9.5	3.5			.544		.121	
10.0	4			.544		.121	
10.5	3.5			.544		.121	
11.0	3	.424	.543	.544	.119	.120	
11.5	2.5			.544		.120	
12.0	2			.544		.120	
12.5	1.5			.544		.120	
13.0	1			.544		.120	
13.5	.5	.425		.545		.120	
14.0	0	.425	.544	.545	.119	.120	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 29

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH •	DEPTH MODEL IN PLACE	
		FLUME BOT TOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.534	.534	.114	.114	$S_0 = .0003$
4.1	9.9			.533		.113	$Q_{01} = .0130$
4.2	9.8			.533		.113	$D_{10} = 4"$
4.3	9.7			.532		.112	Rise = 2"
4.4	9.6			.532		.112	$L = 24"$
4.5	9.5			.532	.114	.112	
5.30	8.70		.534	.532			$Z = 1"$
5.81	8.19			.532E		.112	Weir Height =
6.0	8		.534				$h^* = .001'$
6.32	7.68			.532E		.112	$\Delta h = .003'$
6.50	7.5		.534	.532		.112	
6.6	7.4			.532		.112	
6.7	7.3			.533		.113	Bridge =
6.8	7.2			.533		.113	Position
6.9	7.1			.534		.114	Along
7.0	7		.534	.535		.115	Flume
7.1	6.9			.535		.115	EPG-MPG =
7.2	6.8			.535		.115	.045
7.3	6.7			.536		.115	
7.4	6.6			.536		.115	FIG NO
7.5	6.5	.421	.535	.536	.114	.115	
7.6	6.4			.536		.115	
8.0	6		.535	.536	.114	.115	
8.5	5.5		.536	.536	.114	.114	
9.0	5	.422	.536	.536	.114	.114	
10	4	.422	.536	.536	.114	.114	
11.0	3	.422	.536	.536	.114	.114	
12.0	2		.536	.536	.114	.114	
13.0	1		.537	.536	.114	.114	
14	0	.423	.537	.536	.114	.114	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 30

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WITHOUT MODEL	WATER SURFACE MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.422	.538	.538	.116	.116	SoF .0003
5.0	9			.538	.116	.116	Qm .0138
5.7	8.3		.538	.538	.116	.116	Dise 4"
5.8	8.2			.537		.115	Rise 2"
5.9	8.1			.537		.115	L 24"
6.0	8.0			.537		.115	
6.1	7.9			.537		.115	
6.2	7.8			.537		.115	2 1"
6.3	7.7			.537		.115	Ver
6.4	7.6			.536		.114	Hagm
6.5	7.5	.422		.535		.113	n" .002
7.0	7	.423	.539	.534	.116	.112	Δ .007
7.22	6.78			.535E			
7.73	6.37			.536E			Brigh 5.5'
8.25	5.75			.537E			Posit to
8.5	5.5			.538		.116	Along
8.6	5.4			.539		.117	Flume 7.5'
8.7	5.3			.540		.117	± P.M. = 0.2
8.8	5.2			.541		.118	.042
8.9	5.1			.541		.118	P.O. NO 24
9.0	5			.541		.118	
9.5	4.5	.423		.541		.118	
10.0	4	.424		.541		.117	
10.5	3.5			.541		.117	
11.0	3	.424	.540	.541	.116	.117	
11.5	2.5			.541		.117	
12.0	2		.540	.541		.117	
12.5		.425	.540	.541		.117	
13.0	1		.541	.541	.116	.116	
13.5							
14.0	0	.425	.541		.116	.116	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 31

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.422	.538	.538	.116	.116	$S_0 = .0003$
5.0	9			.538	.116	.116	$Q_m = .0138$
6.0	8			.538	.116	.116	Dia = 5"
6.1	7.9						Rise = 2.5"
6.2	7.8			.537		.115	L = 24"
6.3	7.7			.536		.114	
6.4	7.6			.534		.113	
6.5	7.5			.534		.113	Z = 1"
6.74	7.26			.535E			Weir Height =
7.0	7	.423	.539		.116		$h^* = .001$
7.24	6.76			.537E			$\Delta h = .007$
8.24	5.76			.539E			
8.5	5.5			.540		.117	Bridge = 5.5'
8.6	5.4			.540		.117	Position to
8.7	5.3			.540		.117	Along
8.8	5.2			.540		.117	Flume 7.5'
9.0	5			.540		.117	
9.5		.424		.541		.117	EPG-M.F.G =
10.0	4			.540		.117	.042
10.5				.541		.117	FIG. NO. 23
11.0	3	.424	.540	.541	.116	.117	
11.5				.541		.117	
12.0	2		.540	.541		.117	
12.5		.425	.541	.541	.116	.116	
13.0	1						
13.5							
14.0	0	.425	.541		.116	.116	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 32

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.535	.535	.115	.115	So= .0003
4.10	9.9			.534		.114	Q <sub>mf</sub> .0138
4.20	9.8			.534		.114	Dia= 5"
4.30	9.7			.534		.114	Rise= 2.5"
4.40	9.6			.534		.114	L= 24"
4.50	9.5		.535	.534	.115	.114	
4.72	9.28			.534E		.114	Z= 1"
5.23	8.77			.534E		.114	Weir Height
5.5	8.50						
6.22	7.78			.534E		.114	
6.5	7.5	.420	.535	.535	.115	.115	h* = .002'
6.6	7.0			.536		.116	Δh = .005'
6.7	7.3			.537		.117	
7.0	7.0			.537		.117	Bridge = 7.5'
7.1	6.9			.537		.117	Position to
7.2	6.8			.537		.117	Along
7.3	6.7			.537		.117	Flume 9.5'
7.5	6.5	.421	.536	.538	.115	.117	EPG-M.F.G:
7.6	6.40	.421	.536	.538	.115	.117	.045
7.75	6.25		.536	.538	.115		FIG NO
8.0	6		.537	.539	.115	.117	
9.0	5	.422	.537	.539		.117	
10.0	4	.422	.537	.539	.115	.117	
11.0	3						
12.0	2	.422	.537	.539	.115	.117	
13.0	1	.423	.538	.539	.115	.116	
14.0	0	.423	.538	.539	.115	.116	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 33

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.422	.541	.541	.119	.119	$S_0 = .0003$
5.0	9						$Q_{cr} = .015$
5.5	8.5	.422	.541	.541	.119	.119	$D_{ia} = 5"$
5.8	8.2			.540		.118	$Rise = 2\frac{1}{2}"$
5.9	8.1			.540		.118	$L = 24"$
6.0	8			.540		.118	
6.1	7.9			.540		.118	
6.2	7.8			.539		.117	$Z = 1"$
6.3	7.7			.538		.116	Weir Height =
6.4	7.6			.537		.115	
6.5	7.5	.423	.542	.537	.119	.116	$h^* = .002$
6.74				.536E		.113	$\Delta h = .007$
7.26				.537E		.116	
7.5							Bridge = 5.5'
7.73				.538E		.115	Position to
8.24	5.76			.539E		.116	Along Flume 7.5'
8.5	5.5			.540		.118	
8.6	5.4			.540		.118	EPG-M.F.G. =
8.7	5.3			.541		.110	.042
8.8	5.2			.542		.119	FIG NO <del>25</del>
8.9	5.1			.542		.119	
9.0	5.0			.543	.119	.120	
9.5				.543		.120	
10.0	4.0			.544		.121	
10.5				.544		.121	
11.0	3.0	.424	.543	.545	.119	.121	
11.5				.545		.121	
12.0	2.0			.545		.121	
12.5				.545		.121	
13.0	1.0			.545		.121	
13.5			.544	.545		.121	
14.0	0	.425	.544	.546	.119	.121	



TABLE 4-1 WATER SURFACE MEASUREMENTS P.34

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.550	.550	.130	.130	S <sub>0</sub> = .0003 Q <sub>m</sub> = .017
4.1	9.9			.549		.129	
4.2	9.8			.548		.128	Dia = 4"
4.3	9.7		.550	.548	.130	.128	
4.4	9.6			.548		.128	Rise = 2"
4.5	9.5			.547		.127	L = 24"
4.55	9.45			.547		.127	
5.0	9		.550		.130		Z- 6/8"
6.0	8		.550		.130		Weir Height =
6.55	7.45			.549		.129	h* = .001'
6.6	7.4			.550		.130	
6.7	7.3			.551		.131	$\Delta h$ = .005'
6.8	7.2			.551		.131	
6.9	7.1			.551		.131	Bridge = 7.45'
7.0	7	.421	.551	.552	.130	.131	
7.1	6.9						Position to Along Flume 9.45'
7.25	6.75			.552		.131	EPG-M.P.G =
7.5	6.5			.552		.131	
7.77	6.23			.552			
8.0	6		.551	.553	.130	.131	FIG. NO.
8.5	5.5			.553		.131	
9.0	5			.553			
10.0	4		.551	.554	.130	.132	
11.0	3	.422	.552	.554	.130	.132	
12.0	2		.552	.554	.130	.132	
13.0	1			.554			
14.0	0	.423	.553	.555	.130	.132	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 35

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
3.7	10.3	.420	.555	.555	.135	.135	$S_o = .0003$
3.8	10.2			.554		.134	$Q_{mf} = .023$
3.9	10.1			.553		.133	$D_{10} = 4"$
4.0	10	.420	.555	.552	.135	.132	Rise = 2"
4.1	9.9						$L = 24"$
4.2	9.8			.552		.132	
4.3	9.7			.552		.132	Z-Weir = 6/8"
5.0	9						Height =
6.0	8						
6.3	7.7			.554		.134	
6.4	7.6			.555		.135	$h^* = .002'$
6.5	7.5			.556		.136	$\Delta h = .005'$
6.6	7.4			.557		.136	
6.75	7.25			.557		.136	Bridge =
7.0	7	.421	.556		.135		Position
7.5				.557		.136	Along
8.0	6.0			.557		.136	Flume
8.5				.558		.137	EPG-MPG =
9.0	5.0			.558		.137	
10.0	4.0	.422	.557	.559	.135	.137	FIG NO.
11.0	3.0						
11.5	2.5			.559		.137	
12.0	2.0			.559		.137	
13.0	1.0						
13.7	.3	.423	.558		.135	.137	
14.0	0	.423	.558	.560	.135	.137	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 36

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOT TOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.561	.561	.141	.141	$S_0 = .0003$
4.1	9.9			.560		.140	$Q_{mf} = .028$
4.3	9.8			.559		.139	Dia = 5"
4.5	9.5			.559		.139	Rise = 2.5"
4.6	9.4			.558		.138	L = 24"
4.7	9.3			.558	.141	.138	
5.0	9						Z- 6/8"
5.5							Weir Height =
6.0	8						
6.5	7.5						
6.7	7.3			.559		.139	$h^* = .002'$
6.8	7.2			.560		.140	$\Delta h = .006'$
6.9	7.1			.561		.141	
7.0	7	.421	.562	.562	.141	.141	Bridge = 7.3'
7.25				.563		.142	Position to
7.50				.563		.142	Along
8.0	6			.564		.143	Flume 9.3'
8.5				.564		.143	EPG-MPG=
9.0	5			.564	.141	.143	
9.5				.564		.143	FIG. NO.
10.0	4			.564		.143	
10.5		.422		.564		.142	
11.0	3	.422	.563	.563	.141	.141	
11.5							
12.0	2	.423	.564	.564		.141	
12.5							
13.0	1		.564	.564		.141	
13.5							
14.0	0	.423	.564	.564	.141	.141	



TABLE 4-1 WATER SURFACE MEASUREMENTS P.37

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.564	.564	.144	.144	$S_o = .0003$
4.20	9.8			.563		.143	$Q_m = .031$
4.3	9.7			.563		.143	Dia = 5"
4.4	9.5			.562		.142	Rise = 2.5"
4.6	9.4			.561		.141	L = 24"
4.70	9.3			.561		.141	
5.0	9				.144		Z = 6/8"
5.5	8.5						Weir =
6.0	8						Height =
6.5	7.5						$h^* = .001'$
6.70	7.3			.563		.143	$\Delta h = .005'$
6.8	7.2			.564		.143	
6.9	7.1			.564		.143	Bridge = 7.3'
7.0	7	.421	.565	.564	.144	.143	Position to
7.1	6.9			.566		.145	Along
7.2	6.8			.566		.145	Flume 9.3'
7.3	6.7			.566		.145	ERG-M.P.G.
7.5	6.6			.566		.145	
8.0	6			.566		.145	FIG. NO.
8.5	5.5			.566		.145	
9.0	5			.567		.145	
9.5	4.5			.567		.145	
10.0	4	.422	.566	.567	.144	.145	
10.5	3.5			.567		.145	
11.0	3		.567	.567		.145	
11.5	2.5			.567		.145	
12.0	2		.567	.567		.145	
12.5	1.5						
13.0	1		.567	.567		.145	
13.5							
14.0	0	.423	.567	.567	.144	.144	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 38

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.530	.530	.110	.110	$S_0 = .0005$
4.1	9.9			.529		.109	$Q_{mf} = .0114$
4.2	9.8			.529		.109	$D_{10} = 7.7"$
4.3	9.7			.529		.109	$Rise = 1.4"$
4.4	9.6			.529		.109	$L = 9.7"$
4.5	9.5	.421	.531	.531	.110	.110	
5.0	9	.421	.531		.110		
5.3	8.7			.531		.110	$Z = 1"$
5.4	8.6			.531		.110	Weir =
5.5	8.5			.532		.111	Hight =
5.6	8.4			.532		.111	$h^* = .001'$
5.7	8.3			.532		.111	$\Delta h = .003'$
5.8	8.2						
5.9	8.1			.533		.111	Bridge = 8.7'
6.0	8	.422	.532	.533	.110	.111	Position to
6.5	7.5		.532	.532	.110	.110	Along
7.0	7	.422	.532	.532	.110	.110	Flume 9.5'
8.0	6		.532	.532			EPG-MPG:
9.0	5	.423	.533	.533	.110	.110	
10.0	4	.423	.533	.533	.110	.110	FIG NO.
11.0	3	.424	.534	.534	.110	.110	
12.0	2	.424	.534	.534	.110	.110	
13.0	1	.424	.534	.534	.110	.110	
14.0	0	.425	.535	.535	.110	.110	



TABLE 4-1 WATER SURFACE MEASUREMENTS P.39

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.528	.528	.108	.108	$S_{01} = .0005$
4.1	9.9			.527		.107	$Q_{01} = .0115$
4.2	9.8			.527		.107	Dia = 4"
4.3	9.7			.527		.107	Rise = 2"
4.4	9.6			.527		.107	L = 24"
4.5	9.5		.528	.527	.108	.107	
5.0	9.00		.528		.108		
5.21	8.79			.527E		.107	1"
5.5	8.5						Wear height
5.72	8.28			.527E		.106	
6.0	8.0	.421	.529		.108		$n = .002$
6.22				.526E		.105	$h = .005$
6.5	7.5		.529	.528	.108	.107	
6.6	7.4			.528	.108	.107	Bridge = 7.5'
6.7	7.3			.528		.107	Position to
6.8	7.2			.527		.108	Along Flume 9.5'
6.9	7.1			.530		.109	
7.0	7.0	.421	.529	.531	.108	.110	ERG-MFG =
7.1	6.9			.531			.040
7.2	6.8			.532			FIG. NO.
7.3	6.7			.532	.108		
7.4	6.6			.532	.108		
7.5	6.5			.532	.108	.110	
8.0	6.0	.422	.530	.532	.108	.110	
8.5	5.5						
9.0	5.0	.422	.530	.532	.108	.1100	
9.5	4.5		.531	.532			
10.0	4.0	.423	.531	.532	.108	.109	
10.5	3.5			.532			
11.0	3.0	.423	.531	.531	.108	.108	
11.5	2.5						
12.0	2.0	.426	.532	.532	.108	.108	
12.5	1.5						
13.0	1.0	.424	.532	.532	.108	.108	
13.5	.5						
14.0	0	.425	.533	.532	.108	.108	





STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4	10	.420	.528	.528	.108	.108	$S_o = .0005$
4.2	9.8			.528		.108	$Q_m = .0115$
4.3	9.7			.527		.107	Dia = 5"
4.4	9.6			.527		.107	Rise = 2.5"
4.5	9.5		.528	.527		.107	L = 24"
4.75	9.25			.527E		.107	
5.0	9	.420	.528	.528E	.108		Z = 1"
5.25				.528E		.107	Weir Height =
5.5	8.50			.528E			
5.74	8.26			.529E		.107	$h^* = .002$
6.0	8	.421	.529		.108		$\Delta h = .004$
6.465	7.76			.528E		.107	
6.5	7.5		.529	.529	.108	.108	Bridge = 7.5
6.6	7.4			.530	.108	.109	Position to
6.7	7.3			.531	.108	.110	Along
6.8	7.2			.531	.108	.110	Flume
6.9	7.1			.531	.108	.110	EPG-M.P.G =
7.0	7.0	.421	.529	.531	.108	.110	.040
7.1				.531			FIG. NO
7.2				.531			
7.3				.531			
7.4				.531			
7.5				.531			
8.0	6.0	.422	.530	.531	.108	.109	
8.5			.530	.531			
9.0	5.0	.422	.530	.531	.108	.109	
9.5							
10.0	4.0	.423	.531	.531	.108	.108	
10.5							
11.0	3.0	.423	.531	.531	.108	.108	
11.5							
12.0	2.0	.424	.532	.532	.108	.108	
12.5							
13.0	1.0	.424	.532	.532	.108	.108	
13.5							
14.0	0	.425	.523	.533	.108	.108	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 37A

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.534	.534	.116	.114	$S_o = .0005$
4.1	9.9			.533		.113	$Q_{mf} = .0137$
4.2	9.8			.533		.113	$D_{10} = 4"$
4.3	9.7			.533		.113	$Rise = 2"$
4.4	9.6			.532		.112	$L = 24"$
4.5	9.5			.531		.111	
5.0	9						$Z = 1"$
5.21	8.79			.530E		.110	Weir Height =
5.5	8.5						
5.72	8.28			.531E		.110	
6.0	8	.421	.535		.114		$n^* = .002$
6.22				.533E		.112	$\Delta h = .006$
6.5	7.5			.535		.114	
6.6	7.4			.536		.115	$Grinding = 7.5'$
6.7	7.3			.537		.117	Position to
6.8	7.2			.537		.117	Along
6.9	7.1			.537		.117	Flume 9.5'
7.0	7			.537		.117	EFS-MPD =
7.2	6.8			.537		.117	.04
7.5	6.5			.537		.117	FIG. NO.
8.0	6.0	.422	.536	.537	.114	.115	
8.5	5.5			.537		.115	
9.0	5.0	.423		.538		.115	
9.5	4.5			.538		.115	
10.0	4.0	.423	.537	.538	.114	.115	
10.5	3.5			.538		.115	
11.0	3.0	.424	.538	.539	.114	.115	
11.5	2.5						
12.0	2.0	.424	.538	.539	.114	.115	
12.5	1.5						
13.0	1.0	.425	.538	.539	.114	.115	
13.5	.5						
14.0	0	.425	.539	.539	.114	.114	





TABLE 2-1 WATER SURFACE MEASUREMENTS P. 30 A

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.534		.114	.114	So = .0005
4.1	9.9		.534	.534		.114	Gnt = .0137
4.2	9.8			.533		.113	Dia = 5"
6.3	9.7			.533		.113	Rise = 2.5"
6.4	9.6			.533		.113	L = 24"
6.5	9.50			.533		.113	
4.75	9.25			.533E		.113	Z = 1"
5.0	9			.532E		.112	Weir =
5.25				.533E		.113	Height =
5.5	8.5						
5.74				.533E		.113	n* = .001
6.0	8	.421	.535		.114	.114	Δh = .004
6.24	7.79			.534		.113	
6.5	7.5			.534		.113	Bridge = 7.5'
6.6	7.4			.534		.113	Position to
6.7	7.3			.535		.114	Along Flume 9.5'
6.8	7.2			.536		.115	
6.9	7.1			.536		.115	EPG-MPG =
7.0	7			.536		.115	.04
7.3	6.8			.536		.115	FIG. NO.
7.5	6.5			.536		.115	
8.0	6	.422	.536	.537	.114	.115	
8.5	5.5			.537		.115	
9.0	5	.423	.537	.537	.114	.114	
9.5	4.5						
10.0	4	.423	.537	.537	.114	.114	
10.5	3.5						
11.0	3			.537		.114	
11.5	2.5						
12.0	2	.424	.538	.538	.114	.114	
12.5	1.5						
13.0	1			.538		.114	
13.5	.5						
14.0	0	.425	.539	.539	.114	.114	





TABLE 4-1 WATER SURFACE MEASUREMENTS P.39

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.535	.535	.115	.115	So= .0005 Q <sub>mf</sub> .0138 Dia= 4" Rise= 2" L= 24"
4.1	9.9			.534		.114	
4.2	9.8			.534		.114	
4.3	9.7			.534		.114	
4.4	9.6			.534		.114	
4.5	9.5			.534		.114	
5.0	9		.535		.115		Z= 1"
5.22	8.78			.534E		.114	Weir
5.73	8.27			.534E		.114	Height =
6.0	8	.421	.536		.115		h* = .002'
6.23	7.77			.534E		.113	Δh= .003'
6.5	7.5			.534		.113	
6.6	7.4			.535		.114	Bridge = 7.5'
6.7	7.3			.536		.115	Position to
6.8	7.2			.538		.117	Along
6.9	7.1						Flume 9.5'
7.0	7			.538	.115	.117	EPG-M.P.G=
7.1	6.9						.053
7.2	6.8						FIG NO
7.3	6.7						
7.4	6.6						
7.5	6.5			.538	.115	.117	
8.0	6	.421	.536	.538		.117	
8.5	5.5			.538			
9.0	5	.422	.537	.538		.116	
9.5	4.5			.538			
10.0	4	.422	.537	.538		.116	
10.5	3.5			.538			
11.0	3	.422	.537	.538	.115	.116	
12.0	2	.423	.538	.538	.115	.115	
13.0	1	.423	.538	.538	.115	.115	
14.0	0	.425	.540	.540	.115	.115	



TABLE 4-1 WATER SURFACE MEASUREMENTS P.40

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.535	.535	.115	.115	So= .0005
4.2	9.8			.535		.115	Q <sub>m</sub> = .0138
4.3	9.7			.534		.114	Dis= 5"
4.4	9.6			.534		.114	Rise= 2.5"
4.50	9.5			.534		.114	L= 24"
4.71	9.29			.534E		.114	
5.0	9		.535		.115		Z= 1"
5.21	8.79			.534E		.114	Weir Height =
6.0	8	.421	.536		.115		
6.21	7.79			.534E		.114	h*= .001'
6.5	7.5			.534		.113	Δh= .002'
6.6	7.4			.535		.114	
6.7	7.3			.536		.115	Bridge = 7.5'
6.8	7.2			.537		.116	Position to
6.9	7.1			.537			Along
7.0	7.0	.421		.537		.116	Flume 9.5'
7.1	6.9			.537			EPG-MPG=
7.2	6.8			.537			.053
7.3	6.7	.421	.536	.537	.115	.116	FIG NO.
7.5	6.5		.536	.537			
8.0	6.0		.536	.537	.115	.116	
8.5	5.5	.422	.537	.537	.115	.115	
9.0	5	.422	.537	.537	.115	.115	
10.0	4	.423	.538	.538	.115	.115	
11.0	3		.538	.538	.115	.115	
12.0	2	.424	.539	.539	.115		
13.0	1			.539	.115	.115	
14.0	0	.425	.540	.540	.115	.115	





2-1 WATER S. TOW. WENT. AREA. P.41

STATION	DISTANCE ALONG FLUME	PLUMET GAGE RECORDS			WATER TEMP.	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE V.L. NOT MODEL	MODEL SURFACE			
1	2	3	4	5	6	7	8
4.0	10	.420	.536	.536	.116	.116	Sp. .0005
4.5	9.5						Q. .015
5.0	9			.536		.116	Dig. 4"
5.5	8.5						Sp. 2"
5.6	8.4		.536	.536	.116	.116	Sp. 24"
5.7	8.3			.535	.115	.115	
5.8	8.2			.535		.115	
5.9	8.1			.534		.114	Z 1"
6.0	8	.421	.537	.534	.116	.113	V. =
6.5	7.5						h. =
6.75	7.25			.534E		.114	h. = .002
7.0	7						h. = .007
7.27	6.73			.534E		.115	
7.5	6.5						Bridg. = 6'
7.72	6.28			.537E		.116	Position to
8.0	6	.422	.538	.538	.116	.116	Along Flume 8'
8.1	5.9			.539		.117	EPG-V F.W.
8.2	5.8			.540		.118	.C4
8.3	5.7			.540		.118	FIG NO.
8.4	5.6			.540		.118	
8.5	5.5			.541		.119	
8.6	5.4			.541		.119	
8.7	5.3						
9.0	5	.423		.541		.118	
9.5	4.5			.541		.118	
10.0	4	.423	.539	.541	.116	.118	
10.5	3.5			.541		.118	
11.0	3			.541		.118	
11.5	2.5			.541			
12.0	2	.424	.540	.541	.116	.117	
12.5	1.5			.541		.117	
13.0	1			.541		.117	
13.5	.5	.425	.541	.541	.116	.116	
14.0	0	.425	.541		.116	.116	



TABLE 4-1 WATER SURFACE MEASUREMENTS P-42

STATION	DISTANCE ALONG FLUME	POINT GAGE READINGS			NORMAL DEPTH	DEPTH MODEL IN FLUME	
		FLUME BOT TOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4	10	.420	.536	.536	.116	.116	$S_o = .0005$
4.5	9.5		.536	.536	.116		$Q_{cr} = .015$
5.0	9		.536	.536	.116	.116	$D_{10} = 5"$
5.5	8.5		.536	.536	.116	.116	$R_{10} = 2.5"$
5.6	8.4		.536	.536	.116	.116	$L = 24"$
5.7	8.3			.535		.115	
5.8	8.2			.535		.115	
5.9	8.1			.534		.114	$Z = 1"$
6.0	8	.421	.537	.534	.116	.114	Weir Height
6.21	7.79			.530E		.109	
6.5	7.5						$R_{10} = .001$
6.715	7.285			.532E		.112	$S_o = .006$
7.0	7						
7.435	6.565			.533E		.112	Bridge to Postage
7.5	6.5						Along Flume
8.0	6	.422		.535		.113	8'
8.1	5.9			.535		.113	
8.2	5.8			.536		.114	$C_F = .04$
8.3	5.7			.538		.116	
8.4	5.6						Fig. 40
8.5	5.5		.538	.539	.116	.117	
8.75	5.25	.423		.540		.117	
9.0	5			.540		.117	
9.5	4.5			.540		.117	
10.0	4	.423	.539	.540	.116	.117	
10.5	3.5			.541			
11.0	3			.541		.117	
11.5	2.5	.424		.541		.117	
12.0	2	.424	.540	.541	.116	.117	
12.5	1.5			.541			
13.0	1	.425	.541	.541	.116	.116	
13.5	.5						
14.0	0	.425	.541	.541	.116	.116	
14.5							



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 43

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER WITHOUT MODEL	SURFACE MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.421	.548	.548	.127	.127	$S_0 = .0005$
4.1	9.9		.548	.543		.127	$Q_{inf} .017$
4.2	9.8			.548		.127	$D_{10} = 7.7''$
4.3	9.7			.547		.126	Rise = 1.4"
4.5	9.50			.546		.125	$L = 9.9''$
4.75	9.25			.546		.125	
5.0	9						$Z = 1''$
5.55	8.45			.548		.126	Weir =
5.60	8.40			.548		.126	Height =
5.65	8.35			.548		.126	$h^* = .002'$
5.70	8.3			.548		.126	$\Delta h = .004'$
5.80	8.2			.548		.126	
5.90	8.1			.549		.127	Bridge .8.45'
6.0	8	.422	.549	.549	.127	.127	Position to
6.5	7.5			.550		.128	Along
7.0	7			.550		.128	Flume 9.25'
7.5	6.5			.551		.129	EPG-MPG:
8.0	6	.423	.550	.552	.127	.129	
9.0	5		.550	.552		.129	FIG NO
10.0	4	.424	.551	.553	.127	.129	
11.0	3			.553		.129	
12.0	2	.425	.552	.554	.127	.129	
12.5							
13.0	1			.554		.129	
14.0	0	.426	.553	.555	.127	.129	





TABLE C-1 WATER SURFACE MEASUREMENTS P.44

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.421	.562	.562	.141	.141	$S_o = .0005$
4.5							$Q_n = .031$
5.0	9						$D_o = 5"$
5.5							$Rise = 2.5"$
6.0	8	.422	.563	.563	.141	.141	$L = 24"$
6.1	7.9			.563		.141	
6.3	7.7			.562		.140	
6.5	7.5			.562		.140	$Z = 6/8"$
6.8	7.2			.562		.140	Weir Height =
7.0	7			.561		.139	
7.2	6.8			.560		.138	$h^* = .002'$
8.0	6	.423	.564		.141		$\Delta b = .006'$
9.0	5						
9.2	4.8			.565	.141	.142	Bridge = 4.8'
9.3	4.7			.566		.143	Position to
9.4	4.6			.566		.143	Along
9.5	4.5			.567		.144	Flume 6.8'
9.6	4.4			.566			EDGE-MPG
10.0	4	.424	.565	.566	.141	.142	
10.5	3.5			.566		.142	FIG NO
10.8	3.2			.566			
11.0	3			.566		.142	
12.0	2	.425	.566	.566	.141	.141	
13.0	1	.425	.566	.566	.141	.141	
14	0	.426	.567	.567	.141	.141	



TABLE 4-1 WATER SURFACE MEASUREMENTS P.45

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.421	.571	.571	.150	.150	$S_o = .0005$
4.5				.571			$Q_m = .0379$
5.0	9						Dia = 5"
5.5	8.5	.422		.572		.150	Rise = 2.5"
6.0	8	.422	.572	.572	.150	.150	L = 24"
6.1				.572		.150	
6.2	7.8			.572	.150	.150	
6.3	7.7			.571		.149	Z = 6/8"
6.4	7.6			.570		.148	Weir
6.5	7.5			.569		.147	Height =
6.8	7.2					.147	$h^* = .002'$
7.0	7			.568		.146	$\Delta h = .006'$
7.2	6.8			.568		.146	
8	6	.423	.573				Bridge = 4.8'
8.5	5.5						Position to
9.0	5						Along
9.2	4.8			.573	.150	.150	Flume 6.8'
9.3	4.7			.574		.151	EPG-MPG:
9.4	4.6						
9.5	4.5			.575		.152	FIG NO
9.75	4.25	.424		.576		.152	
10.0	4	.424	.575	.576	.150	.152	
11.0	3	.424		.576	.150	.152	
12.0	2	.425	.575	.576	.150	.151	
13.0	1	.426	.576	.576		.150	
14.0	0	.426	.576		.150	.150	





TABLE 4-1 WATER SURFACE MEASUREMENTS P. 46

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.421	.580	.580	.159	.159	$S_o = .0005$
5.0	9		.580	.580	.159	.159	$Q_{mf} = .042$
6.0	8	.422	.581	.581	.159	.159	Dia = 5"
6.6	7.4			.580		.158	Rise = 2.5"
6.8	7.2			.579		.157	L = 24"
7.0	7			.578		.156	
7.2	6.8			.578		.156	
7.5	6.5						Z = 6/8"
8.0	6	.423	.582		.159		Weir Height =
8.5							$h^* = .002'$
9.0	5						$\Delta h = .005'$
9.2	4.8						
9.225	4.775			.580		.157	
9.3	4.7			.581		.158	Bridge = 4.8'
9.4	4.6			.582		.159	Position to
9.5	4.5			.583		.160	Along Flume 6.3'
10.0	4	.424	.583	.584	.159	.160	EPG-M.P.G =
10.5				.585		.161	
11.0	3			.585		.161	
11.5				.585		.161	FIG NO.
12.0	2	.425	.584		.159		
12.5				.585		.160	
13.0	1			.585		.160	
14.0	0	.426	.585	.585	.159	.159	



TABLE 4-1 WATER SURFACE MEASUREMENTS P. 47

STATION	DISTANCE ALONG FLUME	POINT GAGE READING			NORMAL DEPTH	DEPTH MODEL IN PLACE	
		FLUME BOTTOM	WATER SURFACE				
			WITHOUT MODEL	MODEL IN PLACE			
1	2	3	4	5	6	7	8
4.0	10	.421	.590	.590	.169	.169	S <sub>0</sub> = .0005
4.1	9.9			.589		.168	Q <sub>mf</sub> .0525
4.2	9.8			.589		.168	Dia= 5"
4.3	9.7			.589			Rise= 2.5"
4.4	9.6			.588		.167	L= 24"
4.5	9.5			.587		.166	
4.7	9.3			.587			Z= 6/8"
4.8	9.2			.505		.164	Weir
5.0	9			.583		.162	Height =
6.0	8	.422	.591		.169		h* = .003'
7.0	7			.589	.169	.167	Δh = .01'
7.1	6.9			.592		.170	Bridge = 7'
7.2	6.8			.592		.170	Position to
7.3	6.7						Along
7.4	6.6	.423		.593		.170	Flume 9'
7.5	6.5			.593			EPG-MPG=
8.0	6	.423	.592	.593	.169	.170	
8.5	5.5			.594		.171	
9.0	5			.595		.172	
9.5	4.5			.595		.172	FIG. NO.
10.0	4	.424	.593	.596	.169	.172	
10.5	3.5						
11.0	3			.596			
12.0	2	.425	.594	.597	.169	.172	
13.0	1			.598		.172	
14.0	0	.426	.595	.598	.169	.172	



## Geometry VII

TABLE 4-2 - SMALL FLUME - SEGMENT TESTS - ROUGH BOUNDARIES

(All model tests are two dimensional)

Measured Data					Calculations					
(1) Run No.	(2) Q	(3) Slope	(4) $y_n$	(5) $y_l$	(6) $F_n$	(7) M	(8) $M'$	(9) $C_d$	(10) $y_l/y_n$	(11) $(F_n/M')^{2/3}$
1	0.010	0.00005	0.1116	0.1398	0.0957	.4364	-	.208	1.251	-
2	"	"	"	0.1190	"	.5820	-	.112	1.067	-
3	"	"	"	0.1135	"	.7270	-	.080	1.018	-
4	"	0.0001	0.0848	0.1081	0.1441	.4365	-	.206	1.278	-
5	"	"	"	0.0899	"	.5820	-	.142	1.060	-
6	"	"	"	0.0861	"	.7270	-	.104	1.017	-
7	"	0.0003	0.0672	0.0906	0.2035	.4364	-	.228	1.350	-
8	"	"	"	0.0736	"	.5820	.4650	.171	1.098	0.576
9	"	"	"	0.0697	"	.727	.6194	.129	1.039	0.476
10	"	"	0.0792	0.1050	0.1583	.4364	-	.210	1.325	-
11	"	"	"	0.0841	"	.5820	.4266	.151	1.063	0.518
12	"	"	"	0.0806	"	.7270	.5936	.108	1.019	0.415
13	"	0.0010	0.0580	0.0792	0.2544	.4364	.3247	.254	1.367	0.850
14	"	"	"	0.0653	"	.5820	.4883	.192	1.125	0.648
15	"	"	"	0.0605	"	.7270	.6354	.147	1.042	0.543
16	"	0.0020	0.0526	0.0786	0.2950	.4364	.3421	.254	1.496	0.906
17	"	"	"	0.0623	"	.5820	.4988	.202	1.182	0.704
18	"	"	"	0.0556	"	.7270	.6448	.162	1.059	0.594
19	"	0.0040	0.0467	0.0744	0.3510	.4364	.3592	.266	1.591	0.985
20	"	"	"	0.0583	"	.5820	.5087	.216	1.249	0.781
21	"	"	"	0.0510	"	.7270	.6543	.175	1.091	0.661
22	"	0.0070	0.0380	0.0700	0.4790	.4364	.3766	.280	1.841	1.174
23	"	"	"	0.0548	"	.5820	.5232	.228	1.441	0.943
24	"	"	"	0.0462	"	.7270	.6688	.194	1.217	0.801
25	"	0.0085	0.0343	0.0695	0.5600	.4364	.3827	.282	2.026	1.289
26	"	"	"	0.0536	"	.5820	.5290	.232	1.565	1.039
27	"	"	"	0.0445	"	.7270	.6754	.202	1.299	0.883
28	"	0.0100	0.0311	0.0690	0.6470	.4364	.3880	.286	2.219	1.406
29	"	"	"	0.0523	"	.5820	.5349	.242	1.681	1.135
30	"	"	"	0.0425	"	.7270	.6797	.211	1.368	0.968
31	"	0.0120	0.0290	0.0682	0.7190	.4364	.3910	.287	2.352	1.500
32	"	"	"	0.0521	"	.5820	.5378	.242	1.799	1.214
33	"	"	"	0.0422	"	.7270	.6834	.211	1.457	1.034
34	"	0.0150	0.0277	0.0671	0.7700	.4364	.3932	.292	2.424	1.565
35	"	"	"	0.0510	"	.5820	.5401	.246	1.841	1.267
36	"	"	"	0.0411	"	.7270	.6856	.221	1.485	1.080
37	"	0.0180	0.0265	0.0666	0.8220	.4364	.3954	.295	2.517	1.630
38	"	"	"	0.0504	"	.5820	.5418	.248	1.900	1.321
39	"	"	"	0.0400	"	.7270	.6877	.223	1.510	1.126
40	"	0.0210	0.0251	0.0659	0.8910	.4364	.3976	.296	2.622	1.714
41	"	"	"	0.0495	"	.5820	.5442	.253	1.971	1.389
42	"	"	"	0.0385	"	.7270	.6892	.233	1.533	1.187
43	"	0.0240	0.0235	0.0612	0.9780	.4364	.4006	.322	2.595	1.813
44	"	"	"	0.0470	"	.5820	.5465	.268	1.991	1.475
45	"	"	"	0.0362	"	.7270	.6921	.247	1.533	1.259





(1) Run No.	(2) Q	(3) Slope	(4) $y_n$	(5) $y_l$	(6) $F_n$	(7) M	(8) M'	(9) $C_d$	(10) $y_l/y_n$	(11) $(F_n/M')^{2/3}$
46	0.020	-	0.1526	0.2782	0.1193	.4364	-	-	1.825	-
47	"	-	"	0.1847	"	.5820	-	.207	1.250	-
48	"	-	"	0.1654	"	.7270	-	.121	1.086	-
49	"	0.00005	0.1463	0.2738	0.1269	.4364	-	-	1.870	-
50	"	"	"	0.1847	"	.5820	-	.200	1.260	-
51	"	"	"	0.1589	"	.7270	-	.123	1.084	-
52	"	0.0006	0.1185	0.2444	0.1741	.4364	-	-	2.062	-
53	"	"	"	0.1529	"	.5820	-	.197	1.290	-
54	"	"	"	0.1284	"	.7270	-	.145	1.084	-
55	"	0.0010	0.0974	0.2160	0.2340	.4364	-	-	2.218	-
56	"	"	"	0.1298	"	.5820	-	.212	1.331	-
57	"	"	"	0.1045	"	.7270	.5365	.174	1.072	0.575
58	"	0.0014	0.0811	0.1987	0.3080	.4364	-	-	2.444	-
59	"	"	"	0.1116	"	.5820	.4190	.236	1.374	0.815
60	"	"	"	0.0899	"	.7270	.5874	.199	1.108	0.650
61	"	0.0030	0.0688	0.1876	0.3950	.4364	-	-	2.724	-
62	"	"	"	0.1004	"	.5820	.4604	.256	1.460	0.903
63	"	"	"	0.0803	"	.7270	.6158	.233	1.168	0.744
64	"	0.0050	0.0629	0.1860	0.4510	.4364	-	-	2.960	-
65	"	"	"	0.0964	"	.5820	.4772	.266	1.532	0.963
66	"	"	"	0.0770	"	.7270	.6274	.233	1.224	0.802
67	"	0.0070	0.0567	0.1820	0.5290	.4364	.3295	.972	3.208	1.371
68	"	"	"	0.0937	"	.5820	.4900	.275	1.651	1.052
69	"	"	"	0.0734	"	.7270	.6383	.245	1.291	0.864
70	"	0.0090	0.0500	0.1803	0.6380	.4364	.3500	.866	3.606	1.485
71	"	"	"	0.0921	"	.5820	.5034	.261	1.842	1.172
72	"	"	"	0.0723	"	.7270	.6485	.248	1.447	0.989
73	"	0.0110	0.0459	0.1792	0.7230	.4364	.3609	.824	3.908	1.588
74	"	"	"	0.0912	"	.5820	.5104	.280	1.989	1.261
75	"	"	"	0.0706	"	.7270	.6550	.252	1.540	1.068
76	"	0.0140	0.0416	0.1796	0.8360	.4364	.3692	.850	4.310	1.725
77	"	"	"	0.0900	"	.5820	.5174	.284	2.162	1.378
78	"	"	"	0.0697	"	.7270	.6623	.259	1.678	1.168
79	"	0.0180	0.0382	0.1796	0.9510	.4364	.3762	.850	4.700	1.975
80	"	"	"	0.0888	"	.5820	.5226	.286	2.323	1.490
81	"	"	"	0.0670	"	.7270	.6681	.268	1.752	1.265
82	"	0.0220	0.0362	0.1774	1.0320	.4364	.3797	.769	4.900	1.949
83	"	"	"	0.0862	"	.5820	.5255	.296	2.382	1.568
84	"	"	"	0.0625	"	.7270	.6717	.286	1.729	1.332
85	"	0.0240	0.0360	0.1751	1.0410	.4364	.3801	.708	4.870	1.955
86	"	"	"	0.0864	"	.5820	.5267	.294	2.398	1.575
87	"	"	"	0.0614	"	.7270	.6717	.292	1.702	1.340
88	"	0.0260	0.0351	0.1762	1.0800	.4364	.3810	.735	5.026	2.000
89	"	"	"	0.0863	"	.5820	.5279	.296	2.458	1.612
90	"	"	"	0.0625	"	.7270	.6732	.286	1.781	1.370



TABLE 5-1.- DATA FOR NORMAL DEPTH TEST RUNS - ROUGH BOUNDARIES

Run No.	Q	Slope	$V_n$	$V_t$	Temp.
	cfs	ft./ft.	cm.	cm.	F
1	1.0	0.000010	22.91	19.50	71
2	"	0.000075	16.49	12.70	70
3	"	0.000200	13.55	9.70	70
4	"	0.000400	10.90	7.00	70
5	"	0.000700	9.27	5.40	69
6	"	0.001200	7.95	4.20	69
7	"	0.002000	6.96	3.60	69
8	"	0.003500	5.97	3.30	68
9	2.0	0.000025	30.80	25.00	64
10	"	0.000100	23.35	17.00	64
11	"	0.000250	18.60	12.50	66
12	"	0.000500	15.26	9.00	66
13	"	0.000800	13.17	7.00	67
14	"	0.001400	11.17	5.00	67
15	"	0.002500	9.45	3.80	67
16	"	0.004000	8.18	3.00	68
17	3.0	0.000050	39.16	31.00	71
18	"	0.000150	30.90	22.50	70
19	"	0.000300	24.02	15.50	70
20	"	0.000600	19.04	10.60	70
21	"	0.001000	15.99	7.70	72
22	"	0.001600	13.73	5.70	72
23	"	0.003000	11.41	4.00	72
24	"	0.004500	10.07	3.10	72





TABLE 5-2- TESTS FOR THE ROUGHNESS PARAMETER  $\chi$ 

## A) Normal Depth Tests

Run No.	$y_n$ cm.	Q cfs	S	$C/\sqrt{g}$	$y_n/a$	$y_n/\chi$
1	8.66	3.714	0.0125	8.169	6.829	22.548
2	8.44	3.574	"	8.162	6.650	21.976
3	8.05	3.273	"	8.005	6.348	20.960
4	7.72	3.066	"	7.982	6.086	20.095
5	7.07	2.586	"	7.646	5.574	18.405
6	6.06	1.969	"	7.283	4.779	15.778

B) Velocity Profile Data (  $y$  measured from the bottom )

Q = 3.714 cfs ;  $y_n$  = 0.275 ft. ; S = 0.0125 :

$y$ ft.	$y/\chi$	$v$ fps	$v\sqrt{t_o}/\rho$
0.010	0.794	1.89	5.985
0.015	1.190	1.94	6.143
0.020	1.587	2.00	6.333
0.025	1.984	2.17	6.872
0.030	2.381	2.25	7.125
0.035	2.778	2.31	7.315
0.040	3.175	2.42	7.663
0.045	3.571	2.59	8.201
0.050	3.968	2.69	8.518
0.055	4.365	2.74	8.676
0.060	4.762	2.83	8.961
0.065	5.159	2.94	9.310
0.070	5.556	2.99	9.468
0.080	6.349	3.10	9.816
0.090	7.143	3.27	10.355
0.100	7.937	3.38	10.703
0.110	8.730	3.48	11.020
0.120	9.524	3.57	11.305
0.130	10.317	3.65	11.558
0.140	11.111	3.68	11.653
0.160	12.698	3.75	11.875
0.180	14.286	3.86	12.223
0.200	15.873	3.94	12.476
0.220	17.460	4.00	12.666
0.240	19.048	4.06	12.856



GEOMETRY I<sub>0</sub>TABLE 7 - 1 - 1  
OBSERVED AND CALCULATED DATA

Concretion Ratio	Slope $\frac{Z_{1066}}{ft}$	Q cfs	$Z_0$ cm	$Z_1$ max cm	$Z_1$ min cm	R ft	$\frac{W}{V}$	Cd Appendix 2 Equation 2	f	n x10	$h_f/4h$	$V^2/2g \phi$
0.5	0	2	23.78	24.53	22.97	5934	25,117	.2087	---	---	.48	.0053
			31.97	33.18	32.03	5762	24,377	.1762	---	---	.55	.0041
			32.88	33.70	32.03	5762	24,377	.1762	.018	.097	.49	.0048
			32.15	33.33	31.17	5762	24,377	.2095	.018	.097	.49	.0048
	25	3	32.15	33.33	31.17	5762	24,377	.2095	.0231	.1276	.51	.0067
			32.02	32.90	31.10	5584	23,606	.2294	.0236	.1341	.51	.0060
			29.63	31.10	28.60	7017	35,565	.2282	.0347	.1544	.48	.0091
			19.86	20.90	18.73	5160	26,188	.2607	.0387	.1177	.56	.0158
	100	3	30.73	32.66	20.19	5531	38,533	.3288	.0288	.1489	.51	.0099
			20.45	23.43	17.70	5280	50,555	.4318	.0227	.1255	.52	.0407
			12.07	14.72	9.61	3415	28,516	.4329	.0212	.1127	.52	.0397
			15.94	19.45	12.14	4319	40,959	.3807	.0208	.1161	.48	.0904
0.7	250	3	18.77	23.53	13.00	4975	52,860	.4860	.0191	.1115	.42	.0842
			15.94	20.15	10.34	4319	40,959	.4653	.0194	.1115	.42	.0842
			13.57	18.07	9.34	3704	29,885	.4653	.0194	.1115	.42	.0842
			9.25	13.57	7.67	2704	29,885	.3888	.0202	.1107	.45	.0255
	500	3	12.38	18.09	7.67	3480	42,813	.4685	.0138	.0920	.47	.0800
			13.24	21.45	4.04	3486	56,270	.4685	.0138	.0920	.47	.0800
			23.78	23.93	23.46	5934	25,117	.1506	---	---	.32	.0053
			33.97	34.18	33.57	7688	42,697	.1357	---	---	.34	.0041
	0	3	41.46	43.76	40.93	8783	42,697	.1357	---	---	.36	.0040
			22.88	23.08	22.58	5762	25,377	.1562	.0128	.0937	.40	.0060
			32.15	32.34	31.72	7400	34,795	.1466	.0145	.1060	.31	.0048
			40.14	40.41	39.63	8600	43,180	.1446	.0148	.1144	.35	.0044
0.9	250	3	22.02	26.22	21.71	5594	25,686	.1668	.0231	.1276	.39	.0087
			20.45	24.22	19.11	7053	35,590	.1625	.0235	.1319	.41	.0075
			18.77	20.86	17.43	5762	25,377	.1517	.0249	.1406	.38	.0054
			13.57	18.07	9.34	3704	29,885	.3888	.0194	.1115	.42	.0842
	500	3	12.38	18.09	7.67	3480	42,813	.4685	.0138	.0920	.47	.0800
			13.24	21.45	4.04	3486	56,270	.4685	.0138	.0920	.47	.0800
			23.78	23.93	23.46	5934	25,117	.1506	---	---	.32	.0053
			33.97	34.18	33.57	7688	42,697	.1357	---	---	.34	.0041
	0	3	41.46	43.76	40.93	8783	42,697	.1357	---	---	.36	.0040
			22.88	23.08	22.58	5762	25,377	.1562	.0128	.0937	.40	.0060
			32.15	32.34	31.72	7400	34,795	.1466	.0145	.1060	.31	.0048
			40.14	40.41	39.63	8600	43,180	.1446	.0148	.1144	.35	.0044
0.9	250	3	22.02	26.22	21.71	5594	25,686	.1668	.0231	.1276	.39	.0087
			20.45	24.22	19.11	7053	35,590	.1625	.0235	.1319	.41	.0075
			18.77	20.86	17.43	5762	25,377	.1517	.0249	.1406	.38	.0054
			13.57	18.07	9.34	3704	29,885	.3888	.0194	.1115	.42	.0842
	500	3	12.38	18.09	7.67	3480	42,813	.4685	.0138	.0920	.47	.0800
			13.24	21.45	4.04	3486	56,270	.4685	.0138	.0920	.47	.0800
			23.78	23.93	23.46	5934	25,117	.1506	---	---	.32	.0053
			33.97	34.18	33.57	7688	42,697	.1357	---	---	.34	.0041
	0	3	41.46	43.76	40.93	8783	42,697	.1357	---	---	.36	.0040
			22.88	23.08	22.58	5762	25,377	.1562	.0128	.0937	.40	.0060
			32.15	32.34	31.72	7400	34,795	.1466	.0145	.1060	.31	.0048
			40.14	40.41	39.63	8600	43,180	.1446	.0148	.1144	.35	.0044



GEOMETRY I<sub>0</sub>

TABLE 7-1-2 BAY DATA - LARGE FUME - SMOOTH BOUNDARIES P. 1

(Semi-circular Model Tests)

Run No. 13	Run No. 23	Run No. 33	Run No. 43	Run No. 53	Run No. 63	Run No. 73	Run No. 83	Run No. 93	Run No. 103	Run No. 113	Run No. 123	Run No. 133	Run No. 143	Run No. 153	Run No. 163	Run No. 173	Run No. 183
Q - 1 cfs	Q - 1 cfs	Q - 1 cfs	Q - 1 cfs	Q - 1 cfs	Q - 1 cfs	Q - 1 cfs	Q - 1 cfs	Q - 1 cfs	Q - 2 cfs	Q - 2 cfs	Q - 2 cfs	Q - 2 cfs	Q - 2 cfs	Q - 2 cfs	Q - 2 cfs	Q - 2 cfs	Q - 2 cfs
$Y_n = 15.6$ cm.	$Y_n = 9.42$ cm.	$Y_n = 7.50$ cm.	$Y_n = 6.10$ cm.	$Y_n = 5.11$ cm.	$Y_n = 4.31$ cm.	$Y_n = 4.06$ cm.	$Y_n = 3.60$ cm.	$Y_n = 3.03$ cm.	$Y_n = 2.69$ cm.	$Y_n = 2.65$ cm.	$Y_n = 2.65$ cm.	$Y_n = 2.65$ cm.	$Y_n = 2.65$ cm.	$Y_n = 2.65$ cm.	$Y_n = 2.65$ cm.	$Y_n = 2.65$ cm.	$Y_n = 2.65$ cm.
$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$	$H = b/B = 0.300$
$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$	$L/b = 0.0$
Slope = 0.000281	Slope = 0.000319	Slope = 0.000386	Slope = 0.000530	Slope = 0.000853	Slope = 0.001260	Slope = 0.001790	Slope = 0.00229	Slope = 0.00308	Slope = 0.00390	Slope = 0.00472	Slope = 0.00554	Slope = 0.00636	Slope = 0.00718	Slope = 0.00800	Slope = 0.00882	Slope = 0.00964	Slope = 0.01046
Temp. = 63F	Temp. = 63F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F	Temp. = 64F
Model Sta. = 34.39	Model Sta. = 35.79	Model Sta. = 35.85	Model Sta. = 31.19	Model Sta. = 32.24	Model Sta. = 31.87	Model Sta. = 34.50	Model Sta. = 33.91	Model Sta. = 33.95	Model Sta. = 34.19	Model Sta. = 34.43	Model Sta. = 34.67	Model Sta. = 34.91	Model Sta. = 35.15	Model Sta. = 35.39	Model Sta. = 35.63	Model Sta. = 35.87	Model Sta. = 36.11
Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.
Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)
20.0	13.78	20.0	12.60	20.0	12.46	20.0	12.29	20.0	12.29	20.0	12.29	20.0	12.29	20.0	12.29	20.0	12.29
24.0	17.58	24.0	16.40	24.0	15.22	24.0	14.04	24.0	12.86	24.0	11.68	24.0	10.50	24.0	9.32	24.0	8.14
28.0	21.38	28.0	19.20	28.0	18.02	28.0	16.84	28.0	15.66	28.0	14.48	28.0	13.30	28.0	12.12	28.0	10.94
30.0	17.58	30.0	13.08	30.0	12.67	30.0	12.26	30.0	11.85	30.0	11.44	30.0	11.03	30.0	10.62	30.0	10.21
31.0	31.0	31.0	13.07	31.0	12.66	31.0	12.25	31.0	11.84	31.0	11.43	31.0	11.02	31.0	10.61	31.0	10.20
32.0	17.58	32.0	13.07	32.0	12.66	32.0	12.25	32.0	11.84	32.0	11.43	32.0	11.02	32.0	10.61	32.0	10.20
33.0	31.0	33.0	13.07	33.0	12.66	33.0	12.25	33.0	11.84	33.0	11.43	33.0	11.02	33.0	10.61	33.0	10.20
34.0	17.58	34.0	13.07	34.0	12.66	34.0	12.25	34.0	11.84	34.0	11.43	34.0	11.02	34.0	10.61	34.0	10.20
35.0	31.0	35.0	13.07	35.0	12.66	35.0	12.25	35.0	11.84	35.0	11.43	35.0	11.02	35.0	10.61	35.0	10.20
36.0	17.58	36.0	13.07	36.0	12.66	36.0	12.25	36.0	11.84	36.0	11.43	36.0	11.02	36.0	10.61	36.0	10.20
37.0	31.0	37.0	13.07	37.0	12.66	37.0	12.25	37.0	11.84	37.0	11.43	37.0	11.02	37.0	10.61	37.0	10.20
38.0	17.58	38.0	13.07	38.0	12.66	38.0	12.25	38.0	11.84	38.0	11.43	38.0	11.02	38.0	10.61	38.0	10.20
39.0	31.0	39.0	13.07	39.0	12.66	39.0	12.25	39.0	11.84	39.0	11.43	39.0	11.02	39.0	10.61	39.0	10.20
40.0	17.58	40.0	13.07	40.0	12.66	40.0	12.25	40.0	11.84	40.0	11.43	40.0	11.02	40.0	10.61	40.0	10.20
41.0	31.0	41.0	13.07	41.0	12.66	41.0	12.25	41.0	11.84	41.0	11.43	41.0	11.02	41.0	10.61	41.0	10.20
42.0	17.58	42.0	13.07	42.0	12.66	42.0	12.25	42.0	11.84	42.0	11.43	42.0	11.02	42.0	10.61	42.0	10.20
43.0	31.0	43.0	13.07	43.0	12.66	43.0	12.25	43.0	11.84	43.0	11.43	43.0	11.02	43.0	10.61	43.0	10.20
44.0	17.58	44.0	13.07	44.0	12.66	44.0	12.25	44.0	11.84	44.0	11.43	44.0	11.02	44.0	10.61	44.0	10.20
45.0	31.0	45.0	13.07	45.0	12.66	45.0	12.25	45.0	11.84	45.0	11.43	45.0	11.02	45.0	10.61	45.0	10.20
46.0	17.58	46.0	13.07	46.0	12.66	46.0	12.25	46.0	11.84	46.0	11.43	46.0	11.02	46.0	10.61	46.0	10.20
47.0	31.0	47.0	13.07	47.0	12.66	47.0	12.25	47.0	11.84	47.0	11.43	47.0	11.02	47.0	10.61	47.0	10.20
48.0	17.58	48.0	13.07	48.0	12.66	48.0	12.25	48.0	11.84	48.0	11.43	48.0	11.02	48.0	10.61	48.0	10.20
49.0	31.0	49.0	13.07	49.0	12.66	49.0	12.25	49.0	11.84	49.0	11.43	49.0	11.02	49.0	10.61	49.0	10.20
50.0	17.58	50.0	13.07	50.0	12.66	50.0	12.25	50.0	11.84	50.0	11.43	50.0	11.02	50.0	10.61	50.0	10.20
51.0	31.0	51.0	13.07	51.0	12.66	51.0	12.25	51.0	11.84	51.0	11.43	51.0	11.02	51.0	10.61	51.0	10.20
52.0	17.58	52.0	13.07	52.0	12.66	52.0	12.25	52.0	11.84	52.0	11.43	52.0	11.02	52.0	10.61	52.0	10.20
53.0	31.0	53.0	13.07	53.0	12.66	53.0	12.25	53.0	11.84	53.0	11.43	53.0	11.02	53.0	10.61	53.0	10.20
54.0	17.58	54.0	13.07	54.0	12.66	54.0	12.25	54.0	11.84	54.0	11.43	54.0	11.02	54.0	10.61	54.0	10.20
55.0	31.0	55.0	13.07	55.0	12.66	55.0	12.25	55.0	11.84	55.0	11.43	55.0	11.02	55.0	10.61	55.0	10.20
56.0	17.58	56.0	13.07	56.0	12.66	56.0	12.25	56.0	11.84	56.0	11.43	56.0	11.02	56.0	10.61	56.0	10.20
57.0	31.0	57.0	13.07	57.0	12.66	57.0	12.25	57.0	11.84	57.0	11.43	57.0	11.02	57.0	10.61	57.0	10.20
58.0	17.58	58.0	13.07	58.0	12.66	58.0	12.25	58.0	11.84	58.0	11.43	58.0	11.02	58.0	10.61	58.0	10.20
59.0	31.0	59.0	13.07	59.0	12.66	59.0	12.25	59.0	11.84	59.0	11.43	59.0	11.02	59.0	10.61	59.0	10.20
60.0	17.58	60.0	13.07	60.0	12.66	60.0	12.25	60.0	11.84	60.0	11.43	60.0	11.02	60.0	10.61	60.0	10.20
61.0	31.0	61.0	13.07	61.0	12.66	61.0	12.25	61.0	11.84	61.0	11.43	61.0	11.02	61.0	10.61	61.0	10.20
62.0	17.58	62.0	13.07	62.0	12.66	62.0	12.25	62.0	11.84	62.0	11.43	62.0	11.02	62.0	10.61	62.0	10.20
63.0	31.0	63.0	13.07	63.0	12.66	63.0	12.25	63.0	11.84	63.0	11.43	63.0	11.02	63.0	10.61	63.0	10.20
64.0	17.58	64.0	13.07	64.0	12.66	64.0	12.25	64.0	11.84	64.0	11.43	64.0	11.02	64.0	10.61	64.0	10.20
65.0	31.0	65.0	13.07	65.0	12.66	65.0	12.25	65.0	11.84	65.0	11.43	65.0	11.02	65.0	10.61	65.0	10.20
66.0	17.58	66.0	13.07	66.0	12.66	66.0	12.25	66.0	11.84	66.0	11.43	66.0	11.02	66.0	10.61	66.0	10.20
67.0	31.0	67.0	13.07	67.0	12.66	67.0	12.25	67.0	11.84	67.0	11.43	67.0	11.02	67.0	10.61	67.0	10.20
68.0	17.58	68.0	13.07	68.0	12.66	68.0	12.25	68.0	11.84	68.0	11.43	68.0	11.02	68.0	10.61	68.0	10.20
69.0	31.0	69.0	13.07	69.0	12.66	69.0	12.25	69.0	11.84	69.0	11.43	69.0	11.02	69.0	10.61	69.0	10.20
70.0	17.58	70.0	13.07	70.0	12.66	70.0	12.25	70.0	11.84	70.0	11.43	70.0	11.02	70.0	10.61	70.0	10.20
71.0	31.0	71.0	13.07	71.0	12.66	71.0	12.25	71.0	11.84	71.0	11.43	71.0	11.02	71.0	10.61	71.0	10.20
72.0	17.58	72.0	13.07	72.0	12.66	72.0	12.25	72.0	11.84	72.0	11.43	72.0	11.02	72.0	10.61	72.0	10.20
73.0	31.0	73.0	13.07	73.0	12.66	73.0	12.25	73.0	11.84	73.0	11.43	73.0	11.02	73.0	10.61	73.0	10.20
74.0	17.58	74.0	13.07	74.0	12.66	74.0	12.25	74.0	11.84	74.0	11.43	74.0	11.02	74.0	10.61	74.0	10.20
75.0	31.0	75.0	13.07	75.0	12.66	75.0	12.25	75.0	11.84	75.0	11.43	75.0	11.02	75.0	10.61	75.0	10.20
76.0	17.58	76.0	13.07	76.0	12.66	76.0	12.25	76.0	11.84	76.0	11.43	76.0	11.02	76.0	10.61	76.0	10.20
77.0	31.0	77.0	13.07	77.0	12.66	77.0	12.25	77.0	11.84	77.0	11.43	77.0	11.02	77.0	10.61	77.0	10.20
78.0	17.58	78.0	13.07	78.0	12.66	78.0	12.25	78.0	11.84	78.0	11.43	78.0	11.02	78.0	10.61	78.0	10.20
79.0	31.0	79.0	13.07	79.0	12.66	79.0	12.25	79.0	11.84	79.0	11.43	79.0	11.02	79.0	10.61	79.0	10.20
80.0	17.58	80.0	13.07	80.0	12.66	80.0	12.25	80.0	11.84	80.0	11.43	80.0	11.02	80.0	10.61	80.0	10.20
81.0	31.0	81.0	13.07	81.0	12.66	81.0	12.25	81.0	11.84	81.0	11.43	81.0	11.02	81.0	10.61	81.0	10.20





TABLE 7-1-2 RUN DATA - LARGE FLUME - SMOOTH BOUNDARIES (continued) P. 2

(Semicircular Model Tests)

Run No. 195 q - 2 cfs Y <sub>n</sub> = 16.46m H = 16.46m L/b = 0.0 Slope = 0.00010 Temp. = 67F Model Sta. = 32.42	Run No. 205 q - 2 cfs Y <sub>n</sub> = 16.46m H = 16.46m L/b = 0.0 Slope = 0.00010 Temp. = 67F Model Sta. = 31.58	Run No. 215 q - 2 cfs Y <sub>n</sub> = 16.46m H = 16.46m L/b = 0.0 Slope = 0.00010 Temp. = 66F Model Sta. = 33.10	Run No. 225 q - 2 cfs Y <sub>n</sub> = 9.71m H = 9.71m L/b = 0.0 Slope = 0.000066 Temp. = 66F Model Sta. = 33.87	Run No. 235 q - 2 cfs Y <sub>n</sub> = 9.71m H = 9.71m L/b = 0.0 Slope = 0.000066 Temp. = 66F Model Sta. = 34.40	Run No. 245 q - 2 cfs Y <sub>n</sub> = 9.71m H = 9.71m L/b = 0.0 Slope = 0.000066 Temp. = 66F Model Sta. = 33.86	Run No. 255 q - 2 cfs Y <sub>n</sub> = 9.71m H = 9.71m L/b = 0.0 Slope = 0.000066 Temp. = 67F Model Sta. = 33.87	Run No. 265 q - 2 cfs Y <sub>n</sub> = 8.68m H = 8.68m L/b = 0.0 Slope = 0.000068 Temp. = 67F Model Sta. = 33.65	Run No. 275 q - 2 cfs Y <sub>n</sub> = 8.68m H = 8.68m L/b = 0.0 Slope = 0.000068 Temp. = 68F Model Sta. = 33.34	
Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	
(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	
20.0	16.80	20.0	16.49	20.0	13.69	20.0	9.86	20.0	10.46
24.0	17.81	24.0	16.47	24.0	13.67	24.0	9.85	28.0	10.50
28.0	17.80	28.0	16.75	28.0	13.70	28.0	9.87	30.0	10.50
29.0	17.81	29.0	16.46	29.0	13.69	30.0	9.87	31.0	10.48
30.0	17.81	30.0	16.47	30.0	13.70	30.0	9.87	32.0	10.46
30.5	17.77	29.5	16.72	31.0	13.76	31.0	9.87	33.0	10.46
31.0	17.77	30.0	16.72	31.5	13.76	31.5	9.87	34.0	6.94
31.5	17.77	30.5	16.47	32.0	13.76	32.0	9.85	35.0	6.76
32.0	17.77	31.0	16.47	32.5	13.76	32.5	9.85	36.0	
32.5	17.77	31.5	16.47	33.0	13.76	33.0	9.85	37.0	
33.0	17.77	32.0	16.40	33.5	13.76	33.5	9.47		2.85
33.5	17.77	32.5	16.37	34.0	13.76	34.0	9.47		
34.0	17.77	33.0	16.37	34.5	13.76	34.5	9.47		
34.5	17.77	33.5	16.37	35.0	13.76	35.0	9.53		
35.0	17.77	34.0	16.35		4.72	36.0	9.53		
35.5	17.77	34.5	16.35		4.72	37.0	9.53		
36.0	17.77	35.0	16.34		5.05	38.0	9.53		
36.5	17.77	35.5	16.36			39.0	8.09		8.34
						40.0	8.09		
						41.0	8.09		
						42.0	8.09		
						43.0	8.09		
						44.0	8.09		
						45.0	8.09		
						46.0	8.09		
						47.0	8.09		
						48.0	8.09		
						49.0	8.09		
						50.0	8.09		
						51.0	8.09		
						52.0	8.09		
						53.0	8.09		
						54.0	8.09		
						55.0	8.09		
						56.0	8.09		
						57.0	8.09		
						58.0	8.09		
						59.0	8.09		
						60.0	8.09		
						61.0	8.09		
						62.0	8.09		
						63.0	8.09		
						64.0	8.09		
						65.0	8.09		
						66.0	8.09		
						67.0	8.09		
						68.0	8.09		
						69.0	8.09		
						70.0	8.09		
						71.0	8.09		
						72.0	8.09		
						73.0	8.09		
						74.0	8.09		
						75.0	8.09		
						76.0	8.09		
						77.0	8.09		
						78.0	8.09		
						79.0	8.09		
						80.0	8.09		
						81.0	8.09		
						82.0	8.09		
						83.0	8.09		
						84.0	8.09		
						85.0	8.09		
						86.0	8.09		
						87.0	8.09		
						88.0	8.09		
						89.0	8.09		
						90.0	8.09		
						91.0	8.09		
						92.0	8.09		
						93.0	8.09		
						94.0	8.09		
						95.0	8.09		
						96.0	8.09		
						97.0	8.09		
						98.0	8.09		
						99.0	8.09		
						100.0	8.09		

Run No. 285 q - 2 cfs Y <sub>n</sub> = 8.89 H = 8.89 L/b = 0.0 Slope = 0.000628 Temp. = 67F Model Sta. = 33.44	Run No. 295 q - 2 cfs Y <sub>n</sub> = 8.29 H = 8.29 L/b = 0.0 Slope = 0.000779 Temp. = 66F Model Sta. = 33.83	Run No. 305 q - 2 cfs Y <sub>n</sub> = 8.29 H = 8.29 L/b = 0.0 Slope = 0.000779 Temp. = 66F Model Sta. = 34.17	Run No. 315 q - 2 cfs Y <sub>n</sub> = 8.29 H = 8.29 L/b = 0.0 Slope = 0.000779 Temp. = 66F Model Sta. = 33.62	Run No. 325 q - 2 cfs Y <sub>n</sub> = 8.29 H = 8.29 L/b = 0.0 Slope = 0.000779 Temp. = 66F Model Sta. = 34.85	Run No. 335 q - 2 cfs Y <sub>n</sub> = 7.35 H = 7.35 L/b = 0.0 Slope = 0.000115 Temp. = 67F Model Sta. = 34.35	Run No. 345 q - 2 cfs Y <sub>n</sub> = 7.35 H = 7.35 L/b = 0.0 Slope = 0.000115 Temp. = 67F Model Sta. = 34.56	Run No. 355 q - 2 cfs Y <sub>n</sub> = 7.35 H = 7.35 L/b = 0.0 Slope = 0.000115 Temp. = 67F Model Sta. = 34.23	Run No. 365 q - 2 cfs Y <sub>n</sub> = 7.35 H = 7.35 L/b = 0.0 Slope = 0.000115 Temp. = 67F Model Sta. = 34.02	
Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	Cent. Sta.	
(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	(ft.)	
20.0	20.65	20.0	20.65	20.0	20.65	20.0	20.65	20.0	20.65
24.0	20.77	24.0	20.77	24.0	20.77	24.0	20.77	24.0	20.77
28.0	20.77	28.0	20.77	28.0	20.77	28.0	20.77	28.0	20.77
30.0	20.83	30.0	20.83	30.0	20.83	30.0	20.83	30.0	20.83
31.0	20.83	31.0	20.83	31.0	20.83	31.0	20.83	31.0	20.83
31.5	20.83	31.5	20.83	31.5	20.83	31.5	20.83	31.5	20.83
32.0	20.83	32.0	20.83	32.0	20.83	32.0	20.83	32.0	20.83
32.5	20.83	32.5	20.83	32.5	20.83	32.5	20.83	32.5	20.83
33.0	20.83	33.0	20.83	33.0	20.83	33.0	20.83	33.0	20.83
33.5	20.83	33.5	20.83	33.5	20.83	33.5	20.83	33.5	20.83
34.0	20.83	34.0	20.83	34.0	20.83	34.0	20.83	34.0	20.83
34.5	20.83	34.5	20.83	34.5	20.83	34.5	20.83	34.5	20.83
35.0	20.83	35.0	20.83	35.0	20.83	35.0	20.83	35.0	20.83
35.5	20.83	35.5	20.83	35.5	20.83	35.5	20.83	35.5	20.83
36.0	20.83	36.0	20.83	36.0	20.83	36.0	20.83	36.0	20.83
36.5	20.83	36.5	20.83	36.5	20.83	36.5	20.83	36.5	20.83
37.0	20.83	37.0	20.83	37.0	20.83	37.0	20.83	37.0	20.83
37.5	20.83	37.5	20.83	37.5	20.83	37.5	20.83	37.5	20.83
38.0	20.83	38.0	20.83	38.0	20.83	38.0	20.83	38.0	20.83
38.5	20.83	38.5	20.83	38.5	20.83	38.5	20.83	38.5	20.83
39.0	20.83	39.0	20.83	39.0	20.83	39.0	20.83	39.0	20.83
39.5	20.83	39.5	20.83	39.5	20.83	39.5	20.83	39.5	20.83
40.0	20.83	40.0	20.83	40.0	20.83	40.0	20.83	40.0	20.83
40.5	20.83	40.5	20.83	40.5	20.83	40.5	20.83	40.5	20.83
41.0	20.83	41.0	20.83	41.0	20.83	41.0	20.83	41.0	20.83
41.5	20.83	41.5	20.83	41.5	20.83	41.5	20.83	41.5	20.83
42.0	20.83	42.0	20.83	42.0	20.83	42.0	20.83	42.0	20.83
42.5	20.83	42.5	20.83	42.5	20.83	42.5	20.83	42.5	20.83
43.0	20.83	43.0	20.83	43.0	20.83	43.0	20.83	43.0	20.83
43.5	20.83	43.5	20.83	43.5	20.83	43.5	20.83	43.5	20.83
44.0	20.83	44.0	20.83	44.0	20.83	44.0	20.83	44.0	20.83
44.5	20.83	44.5	20.83	44.5	20.83	44.5	20.83	44.5	20.83
45.0	20.83	45.0	20.83	45.0	20.83	45.0	20.83	45.0	20.83
45.5	20.83	45.5	20.83	45.5	20.83	45.5	20.83	45.5	20.83
46.0	20.83	46.0	20.83	46.0	20.83	46.0	20.83	46.0	20.83
46.5	20.83	46.5	20.83	46.5	20.83	46.5	20.83	46.5	20.83
47.0	20.83	47.0	20.83	47.0	20.83	47.0	20.83	47.0	20.83
47.5	20.83	47.5	20.83	47.5	20.83	47.5	20.83	47.5	20.83
48.0	20.83	48.0	20.83	48.0	20.83	48.0	20.83	48.0	20.83
48.5	20.83	48.5	20.83	48.5	20.83	48.5	20.83	48.5	20.83
49.0	20.83	49.0	20.83	49.0	20.83	49.0	20.83	49.0	20.83
49.5	20.83	49.5	20.83	49.5	20.83	49.5	20.83	49.5	20.83
50.0	20.83	50.0	20.83	50.0	20.83	50.0	20.83	50.0	20.83
50.5	20.83	50.5	20.83	50.5	20.83	50.5	20.83	50.5	20.83
51.0	20.83	51.0	20.83	51.0	20.83	51.0	20.83	51.0	20.83
51.5	20.83	51.5	20.83	51.5	20.83	51.5	20.83	51.5	20.83
52.0	20.83	52.0	20.83	52.0	20.83	52.0	20.83	52.0	20.83
52.5	20.83	52.5	20.83	52.5	20.83	52.5	20.83	52.5	20.83
53.0	20.83	53.0	20.83	53.0	20.83	53.0	20.83	53.0	20.83
53.5	20.83	53.5	20.83	53.5	20.83	53.5	20.83	53.5	20.83
54.0	20.83	54.0	20.83	54.0	20.83	54.0	20.83	54.0	20.83
54.5	20.83	54.5	20.83	54.5	20.83	54.5	20.83	54.5	20.83
55.0	20.83	55.0	20.83	55.0	20.83	55.0	20.83	55.0	20.83
55.5	20.83	55.5	20.83	55.5	20.83	55.5	20.83	55.5	20.83
56.0	20.83	56.0	20.83	56.0	20.83	56.0	20.83	56.0	20.83
56.5	20.83	56.5	20.83	56.5	20.83	56.5	20.83	56.5	20.83









TABLE 7-1-2 RAW DATA - LARGE FLUME - SMOOTH BOUNDARIES (continued) P. 4  
(Semicircular Model Tests)

Run No. 55S				Run No. 56S				Run No. 57S				Run No. 58S				Run No. 59S				Run No. 60S				Run No. 61S			
$Q = 3$ cfs				$Q = 3$ cfs				$Q = 3$ cfs				$Q = 3$ cfs				$Q = 3.5$ cfs				$Q = 3.5$ cfs				$Q = 3.5$ cfs			
$Y_n = 33.0$ cm.				$Y_n = 29.68$ cm.				$Y_n = 29.65$ cm.				$Y_n = 29.65$ cm.				$Y_n = 19.44$ cm.				$Y_n = 19.44$ cm.				$Y_n = 19.44$ cm.			
$M = b/B = 0.889$				$M = b/B = 0.491$				$M = b/B = 0.693$				$M = b/B = 0.889$				$M = b/B = 0.491$				$M = b/B = 0.693$				$M = b/B = 0.889$			
$L/b = 0.0$				$L/b = 0.0$				$L/b = 0.0$				$L/b = 0.0$				$L/b = 0.0$				$L/b = 0.0$				$L/b = 0.0$			
Slope = 0.000025				Slope = 0.000050				Slope = 0.000050				Slope = 0.000050				Slope = 0.000185				Slope = 0.000185				Slope = 0.000185			
Temp. = 67°F				Temp. = 66°F				Temp. = 66°F				Temp. = 66°F				Temp. = 70°F				Temp. = 65°F				Temp. = 70°F			
Model Sta. = 34.20				Model Sta. = 34.07				Model Sta. = 33.82				Model Sta. = 33.98				Model Sta. = 34.17				Model Sta. = 34.56				Model Sta. = 33.04			
Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)
20.0	33.09	20.0	30.87	20.0	29.93	20.0	29.69	20.0	22.70	20.0	20.27	20.0	20.27	20.0	20.27	20.0	20.27	20.0	20.27	20.0	20.27	20.0	19.58	20.0	19.58	20.0	19.58
24.0	33.06	24.0	30.87	24.0	29.91	24.0	29.67	24.0	22.68	24.0	20.27	24.0	20.27	24.0	20.27	24.0	20.27	24.0	20.27	24.0	20.27	24.0	19.56	24.0	19.56	24.0	19.56
28.0	33.06	28.0	30.87	28.0	29.91	28.0	29.66	28.0	22.75	28.0	20.27	28.0	20.27	28.0	20.27	28.0	20.27	28.0	20.27	28.0	20.27	28.0	19.55	28.0	19.55	28.0	19.55
30.0	33.06	30.0	30.90	30.0	29.91	30.0	29.66	30.0	22.71	30.0	20.27	30.0	20.27	30.0	20.27	30.0	20.27	30.0	20.27	30.0	20.27	30.0	19.54	30.0	19.54	30.0	19.54
31.0	33.06	31.0	30.89	31.0	29.90	31.0	29.66	31.0	22.72	31.0	20.26	31.0	20.26	31.0	20.26	31.0	20.26	31.0	20.26	31.0	20.26	31.0	19.50	31.0	19.50	31.0	19.50
31.5	33.06	31.5	30.85	31.5	29.89	31.5	29.66	31.5	22.66	31.5	20.24	31.5	20.24	31.5	20.24	31.5	20.24	31.5	20.24	31.5	20.24	31.5	19.49	31.5	19.49	31.5	19.49
32.0	33.05	32.0	30.80	32.0	29.87	32.0	29.64	32.0	22.62	32.0	18.35	32.0	18.35	32.0	18.35	32.0	18.35	32.0	18.35	32.0	18.35	32.0	19.48	32.0	19.48	32.0	19.48
32.5	33.05	32.5	28.82	32.5	29.34	32.5	29.64	32.5	17.35	32.5	36.5	32.5	36.5	32.5	36.5	32.5	36.5	32.5	36.5	32.5	36.5	32.5	19.46	32.5	19.46	32.5	19.46
33.0	33.05	33.0	28.65	33.0	29.23	33.0	29.61	33.0	15.92	33.0	37.0	33.0	37.0	33.0	37.0	33.0	37.0	33.0	37.0	33.0	37.0	33.0	19.25	33.0	19.25	33.0	19.25
36.0	32.98	36.0	28.55	36.0	29.23	36.0	29.55	36.0	16.55	36.0	37.0	36.0	37.0	36.0	37.0	36.0	37.0	36.0	37.0	36.0	37.0	36.0	19.25	36.0	19.25	36.0	19.25
37.0	32.97	37.0	28.56	37.0	29.26	37.0	29.55	37.0	16.55	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	37.0	19.25	37.0	19.25	37.0	19.25
37.5	32.97	37.5	28.60	37.5	29.26	37.5	29.55	37.5	16.55	37.5	37.0	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	19.25	37.5	19.25	37.5	19.25
38.0	33.00	38.0	28.60	38.0	29.26	38.0	29.55	38.0	16.55	38.0	37.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	38.0	19.25	38.0	19.25	38.0	19.25

\*Only the minimum depth was measured on the downstream side of the model.

























TABLE 7-2. RAW DATA - LARGE FLUME - ROUGH BOUNDARIES (continued) P. 4

(Two and Three Dimensional Semicircular Model Tests)

Run No. 5-7 Q - 3 cfs Yn - 13.28 cm. M - b/B = 0.700 L/b = 0.5 Slope = 0.000870 Temp. = 72F Model Sta. = 30.00	Run No. 5-8 Q - 3 cfs Yn - 13.28 cm. M - b/B = 0.700 L/b = 0.5 Slope = 0.000870 Temp. = 72F Model Sta. = 30.00	Run No. 5-9 Q - 2 cfs Yn - 13.28 cm. M - b/B = 0.689 L/b = 0.0 Slope = 0.000870 Temp. = 72F Model Sta. = 30.00	Run No. 5-10 Q - 2 cfs Yn - 13.28 cm. M - b/B = 0.689 L/b = 0.0 Slope = 0.000870 Temp. = 72F Model Sta. = 30.00	Run No. 5-11 Q - 2 cfs Yn - 13.28 cm. M - b/B = 0.900 L/b = 0.0 Slope = 0.000870 Temp. = 74F Model Sta. = 30.00	Run No. 5-12 Q - 2 cfs Yn - 13.28 cm. M - b/B = 0.900 L/b = 1.0 Slope = 0.000870 Temp. = 74F Model Sta. = 30.00	Run No. 6-1 Q - 3 cfs Yn - 15.28 cm. M - b/B = 0.300 L/b = 0.0 Slope = 0.00123 Temp. = 73F Model Sta. = 30.00	Run No. 6-2 Q - 3 cfs Yn - 15.28 cm. M - b/B = 0.311 L/b = 0.5 Slope = 0.00123 Temp. = 73F Model Sta. = 30.00	Run No. 6-3 Q - 3 cfs Yn - 15.28 cm. M - b/B = 0.311 L/b = 1.0 Slope = 0.00123 Temp. = 73F Model Sta. = 30.00	
Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)
20.0	13.81	20.0	13.71	20.0	13.33	20.0	13.34	20.0	13.34
24.0	13.62	24.0	13.70	24.0	13.33	24.0	13.33	24.0	13.33
28.0	13.43	28.0	13.71	28.0	13.33	28.0	13.33	28.0	13.33
32.0	13.24	32.0	13.72	32.0	13.33	32.0	13.33	32.0	13.33
36.0	13.05	36.0	13.73	36.0	13.33	36.0	13.33	36.0	13.33
40.0	12.86	40.0	13.74	40.0	13.33	40.0	13.33	40.0	13.33
44.0	12.67	44.0	13.75	44.0	13.33	44.0	13.33	44.0	13.33
48.0	12.48	48.0	13.76	48.0	13.33	48.0	13.33	48.0	13.33
52.0	12.29	52.0	13.77	52.0	13.33	52.0	13.33	52.0	13.33
56.0	12.10	56.0	13.78	56.0	13.33	56.0	13.33	56.0	13.33
60.0	11.91	60.0	13.79	60.0	13.33	60.0	13.33	60.0	13.33
64.0	11.72	64.0	13.80	64.0	13.33	64.0	13.33	64.0	13.33
68.0	11.53	68.0	13.81	68.0	13.33	68.0	13.33	68.0	13.33
72.0	11.34	72.0	13.82	72.0	13.33	72.0	13.33	72.0	13.33
76.0	11.15	76.0	13.83	76.0	13.33	76.0	13.33	76.0	13.33
80.0	10.96	80.0	13.84	80.0	13.33	80.0	13.33	80.0	13.33
84.0	10.77	84.0	13.85	84.0	13.33	84.0	13.33	84.0	13.33
88.0	10.58	88.0	13.86	88.0	13.33	88.0	13.33	88.0	13.33
92.0	10.39	92.0	13.87	92.0	13.33	92.0	13.33	92.0	13.33
96.0	10.20	96.0	13.88	96.0	13.33	96.0	13.33	96.0	13.33
100.0	10.01	100.0	13.89	100.0	13.33	100.0	13.33	100.0	13.33
104.0	9.82	104.0	13.90	104.0	13.33	104.0	13.33	104.0	13.33
108.0	9.63	108.0	13.91	108.0	13.33	108.0	13.33	108.0	13.33
112.0	9.44	112.0	13.92	112.0	13.33	112.0	13.33	112.0	13.33
116.0	9.25	116.0	13.93	116.0	13.33	116.0	13.33	116.0	13.33
120.0	9.06	120.0	13.94	120.0	13.33	120.0	13.33	120.0	13.33
124.0	8.87	124.0	13.95	124.0	13.33	124.0	13.33	124.0	13.33
128.0	8.68	128.0	13.96	128.0	13.33	128.0	13.33	128.0	13.33
132.0	8.49	132.0	13.97	132.0	13.33	132.0	13.33	132.0	13.33
136.0	8.30	136.0	13.98	136.0	13.33	136.0	13.33	136.0	13.33
140.0	8.11	140.0	13.99	140.0	13.33	140.0	13.33	140.0	13.33
144.0	7.92	144.0	14.00	144.0	13.33	144.0	13.33	144.0	13.33
148.0	7.73	148.0	14.01	148.0	13.33	148.0	13.33	148.0	13.33
152.0	7.54	152.0	14.02	152.0	13.33	152.0	13.33	152.0	13.33
156.0	7.35	156.0	14.03	156.0	13.33	156.0	13.33	156.0	13.33
160.0	7.16	160.0	14.04	160.0	13.33	160.0	13.33	160.0	13.33
164.0	6.97	164.0	14.05	164.0	13.33	164.0	13.33	164.0	13.33
168.0	6.78	168.0	14.06	168.0	13.33	168.0	13.33	168.0	13.33
172.0	6.59	172.0	14.07	172.0	13.33	172.0	13.33	172.0	13.33
176.0	6.40	176.0	14.08	176.0	13.33	176.0	13.33	176.0	13.33
180.0	6.21	180.0	14.09	180.0	13.33	180.0	13.33	180.0	13.33
184.0	6.02	184.0	14.10	184.0	13.33	184.0	13.33	184.0	13.33
188.0	5.83	188.0	14.11	188.0	13.33	188.0	13.33	188.0	13.33
192.0	5.64	192.0	14.12	192.0	13.33	192.0	13.33	192.0	13.33
196.0	5.45	196.0	14.13	196.0	13.33	196.0	13.33	196.0	13.33
200.0	5.26	200.0	14.14	200.0	13.33	200.0	13.33	200.0	13.33
204.0	5.07	204.0	14.15	204.0	13.33	204.0	13.33	204.0	13.33
208.0	4.88	208.0	14.16	208.0	13.33	208.0	13.33	208.0	13.33
212.0	4.69	212.0	14.17	212.0	13.33	212.0	13.33	212.0	13.33
216.0	4.50	216.0	14.18	216.0	13.33	216.0	13.33	216.0	13.33
220.0	4.31	220.0	14.19	220.0	13.33	220.0	13.33	220.0	13.33
224.0	4.12	224.0	14.20	224.0	13.33	224.0	13.33	224.0	13.33
228.0	3.93	228.0	14.21	228.0	13.33	228.0	13.33	228.0	13.33
232.0	3.74	232.0	14.22	232.0	13.33	232.0	13.33	232.0	13.33
236.0	3.55	236.0	14.23	236.0	13.33	236.0	13.33	236.0	13.33
240.0	3.36	240.0	14.24	240.0	13.33	240.0	13.33	240.0	13.33
244.0	3.17	244.0	14.25	244.0	13.33	244.0	13.33	244.0	13.33
248.0	2.98	248.0	14.26	248.0	13.33	248.0	13.33	248.0	13.33
252.0	2.79	252.0	14.27	252.0	13.33	252.0	13.33	252.0	13.33
256.0	2.60	256.0	14.28	256.0	13.33	256.0	13.33	256.0	13.33
260.0	2.41	260.0	14.29	260.0	13.33	260.0	13.33	260.0	13.33
264.0	2.22	264.0	14.30	264.0	13.33	264.0	13.33	264.0	13.33
268.0	2.03	268.0	14.31	268.0	13.33	268.0	13.33	268.0	13.33
272.0	1.84	272.0	14.32	272.0	13.33	272.0	13.33	272.0	13.33
276.0	1.65	276.0	14.33	276.0	13.33	276.0	13.33	276.0	13.33
280.0	1.46	280.0	14.34	280.0	13.33	280.0	13.33	280.0	13.33
284.0	1.27	284.0	14.35	284.0	13.33	284.0	13.33	284.0	13.33
288.0	1.08	288.0	14.36	288.0	13.33	288.0	13.33	288.0	13.33
292.0	0.89	292.0	14.37	292.0	13.33	292.0	13.33	292.0	13.33
296.0	0.70	296.0	14.38	296.0	13.33	296.0	13.33	296.0	13.33
300.0	0.51	300.0	14.39	300.0	13.33	300.0	13.33	300.0	13.33
304.0	0.32	304.0	14.40	304.0	13.33	304.0	13.33	304.0	13.33
308.0	0.13	308.0	14.41	308.0	13.33	308.0	13.33	308.0	13.33
312.0	0.00	312.0	14.42	312.0	13.33	312.0	13.33	312.0	13.33
316.0	0.00	316.0	14.43	316.0	13.33	316.0	13.33	316.0	13.33
320.0	0.00	320.0	14.44	320.0	13.33	320.0	13.33	320.0	13.33
324.0	0.00	324.0	14.45	324.0	13.33	324.0	13.33	324.0	13.33
328.0	0.00	328.0	14.46	328.0	13.33	328.0	13.33	328.0	13.33
332.0	0.00	332.0	14.47	332.0	13.33	332.0	13.33	332.0	13.33
336.0	0.00	336.0	14.48	336.0	13.33	336.0	13.33	336.0	13.33
340.0	0.00	340.0	14.49	340.0	13.33	340.0	13.33	340.0	13.33
344.0	0.00	344.0	14.50	344.0	13.33	344.0	13.33	344.0	13.33
348.0	0.00	348.0	14.51	348.0	13.33	348.0	13.33	348.0	13.33
352.0	0.00	352.0	14.52	352.0	13.33	352.0	13.33	352.0	13.33
356.0	0.00	356.0	14.53	356.0	13.33	356.0	13.33	356.0	13.33
360.0	0.00	360.0	14.54	360.0	13.33	360.0	13.33	360.0	13.33
364.0	0.00	364.0	14.55	364.0	13.33	364.0	13.33	364.0	13.33
368.0	0.00	368.0	14.56	368.0	13.33	368.0	13.33	368.0	13.33
372.0	0.00	372.0	14.57	372.0	13.33	372.0	13.33	372.0	13.33
376.0	0.00	376.0	14.58	376.0	13.33	376.0	13.33	376.0	13.33
380.0	0.00	380.0	14.59	380.0	13.33	380.0	13.33	380.0	13.33
384.0	0.00	384.0	14.60	384.0	13.33	384.0	13.33	384.0	13.33
388.0	0.00	388.0	14.61	388.0	13.33	388.0	13.33	388.0	13.33
392.0	0.00	392.0	14.62	392.0	13.33	392.0	13.33	392.0	13.33
396.0	0.00	396.0	14.63	396.0	13.33	396.0	13.33	396.0	13.33
400.0	0.00	400.0	14.64	400.0	13.33	400.0	13.33	400.0	13.33
404.0	0.00	404.0	14.65	404.0	13.33	404.0	13.33	404.0	13.33
408.0	0.00	408.0	14.66	408.0	13.33	408.0	13.33	408.0	13.33
412.0	0.00	412.0	14.67	412.0	13.33	412.0	13.33	412.0	13.33
416.0	0.00	416.0	14.68	416.0	13.33	416.0	13.33	416.0	13.33
420.0	0.00	420.0	14.69	420.0	13.33	420.0	13.33	420.0	13.33
424.0	0.00	424.0	14.70	424.0	13.33	424.0	13.33	424.0	13.33
428.0	0.00	428.0	14.71	428.0	13.33	428.0	13.33	428.0	13.33
432.0	0.00	432.0	14.72	432.0	13.33	432.0	13.33	432.0	13.33
436.0	0.00	436.0	14.73	436.0	13.33	436.0	13.33	436.0	13.33
440.0	0.00	440.0	14.74	440.0	13.33	440.0	13.33	440.0	13.33
444.0	0.00	444.0	14.75	444.0	13.33	444.0	13.33	444.0	13.33
448.0	0.00	448.0	14.76	448.0	13.33	448.0	13.33	448.0	13.33
452.0	0.0								



TABLE 7-2. - IAW DATA - LARGE FLUME - RUGH BOUNDARIES (continued) P. 5

(Two and Three Dimensional Semicircular Model Tests)

Run No. 7-1	Run No. 7-2	Run No. 7-3	Run No. 7-4	Run No. 7-5	Run No. 7-6	Run No. 7-7	Run No. 7-8	Run No. 7-9
Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)
Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)
24.0	10.25	25.0	8.79	8.47	24.0	20.0	20.0	24.0
24.0	10.43	26.0	8.91	8.59	25.0	7.45	7.25	25.0
26.0	10.58	27.0	9.03	8.71	26.0	7.58	7.38	26.0
26.0	10.74	28.0	9.15	8.83	27.0	7.70	7.50	27.0
26.0	10.90	29.0	9.27	8.95	28.0	7.82	7.62	28.0
27.0	11.06	30.0	9.39	9.07	29.0	7.94	7.74	29.0
27.0	11.22	31.0	9.51	9.19	30.0	8.06	7.86	30.0
27.5	11.38	32.0	9.63	9.31	31.0	8.18	7.98	31.0
28.0	11.54	33.0	9.75	9.43	32.0	8.30	8.10	32.0
28.0	11.70	34.0	9.87	9.55	33.0	8.42	8.22	33.0
28.0	11.86	35.0	9.99	9.67	34.0	8.54	8.34	34.0
29.0	12.02	36.0	10.11	9.79	35.0	8.66	8.46	35.0
29.0	12.18	37.0	10.23	9.91	36.0	8.78	8.58	36.0
29.0	12.34	38.0	10.35	10.03	37.0	8.90	8.70	37.0
29.0	12.50	39.0	10.47	10.15	38.0	9.02	8.82	38.0
29.0	12.66	40.0	10.59	10.27	39.0	9.14	8.94	39.0
30.0	12.82	41.0	10.71	10.39	40.0	9.26	9.06	40.0
30.0	12.98	42.0	10.83	10.51	41.0	9.38	9.18	41.0
30.0	13.14	43.0	10.95	10.63	42.0	9.50	9.30	42.0
30.0	13.30	44.0	11.07	10.75	43.0	9.62	9.42	43.0
30.0	13.46	45.0	11.19	10.87	44.0	9.74	9.54	44.0
30.0	13.62	46.0	11.31	10.99	45.0	9.86	9.66	45.0
30.0	13.78	47.0	11.43	11.11	46.0	9.98	9.78	46.0
30.0	13.94	48.0	11.55	11.23	47.0	10.10	9.90	47.0
30.0	14.10	49.0	11.67	11.35	48.0	10.22	10.02	48.0
30.0	14.26	50.0	11.79	11.47	49.0	10.34	10.14	49.0
30.0	14.42	51.0	11.91	11.59	50.0	10.46	10.26	50.0
30.0	14.58	52.0	12.03	11.71	51.0	10.58	10.38	51.0
30.0	14.74	53.0	12.15	11.83	52.0	10.70	10.50	52.0
30.0	14.90	54.0	12.27	11.95	53.0	10.82	10.62	53.0
30.0	15.06	55.0	12.39	12.07	54.0	10.94	10.74	54.0
30.0	15.22	56.0	12.51	12.19	55.0	11.06	10.86	55.0
30.0	15.38	57.0	12.63	12.31	56.0	11.18	10.98	56.0
30.0	15.54	58.0	12.75	12.43	57.0	11.30	11.10	57.0
30.0	15.70	59.0	12.87	12.55	58.0	11.42	11.22	58.0
30.0	15.86	60.0	12.99	12.67	59.0	11.54	11.34	59.0
30.0	16.02	61.0	13.11	12.79	60.0	11.66	11.46	60.0
30.0	16.18	62.0	13.23	12.91	61.0	11.78	11.58	61.0
30.0	16.34	63.0	13.35	13.03	62.0	11.90	11.70	62.0
30.0	16.50	64.0	13.47	13.15	63.0	12.02	11.82	63.0
30.0	16.66	65.0	13.59	13.27	64.0	12.14	11.94	64.0
30.0	16.82	66.0	13.71	13.39	65.0	12.26	12.06	65.0
30.0	16.98	67.0	13.83	13.51	66.0	12.38	12.18	66.0
30.0	17.14	68.0	13.95	13.63	67.0	12.50	12.30	67.0
30.0	17.30	69.0	14.07	13.75	68.0	12.62	12.42	68.0
30.0	17.46	70.0	14.19	13.87	69.0	12.74	12.54	69.0
30.0	17.62	71.0	14.31	13.99	70.0	12.86	12.66	70.0
30.0	17.78	72.0	14.43	14.11	71.0	12.98	12.78	71.0
30.0	17.94	73.0	14.55	14.23	72.0	13.10	12.90	72.0
30.0	18.10	74.0	14.67	14.35	73.0	13.22	13.02	73.0
30.0	18.26	75.0	14.79	14.47	74.0	13.34	13.14	74.0
30.0	18.42	76.0	14.91	14.59	75.0	13.46	13.26	75.0
30.0	18.58	77.0	15.03	14.71	76.0	13.58	13.38	76.0
30.0	18.74	78.0	15.15	14.83	77.0	13.70	13.50	77.0
30.0	18.90	79.0	15.27	14.95	78.0	13.82	13.62	78.0
30.0	19.06	80.0	15.39	15.07	79.0	13.94	13.74	79.0
30.0	19.22	81.0	15.51	15.19	80.0	14.06	13.86	80.0
30.0	19.38	82.0	15.63	15.31	81.0	14.18	13.98	81.0
30.0	19.54	83.0	15.75	15.43	82.0	14.30	14.10	82.0
30.0	19.70	84.0	15.87	15.55	83.0	14.42	14.22	83.0
30.0	19.86	85.0	15.99	15.67	84.0	14.54	14.34	84.0
30.0	20.02	86.0	16.11	15.79	85.0	14.66	14.46	85.0
30.0	20.18	87.0	16.23	15.91	86.0	14.78	14.58	86.0
30.0	20.34	88.0	16.35	16.03	87.0	14.90	14.70	87.0
30.0	20.50	89.0	16.47	16.15	88.0	15.02	14.82	88.0
30.0	20.66	90.0	16.59	16.27	89.0	15.14	14.94	89.0
30.0	20.82	91.0	16.71	16.39	90.0	15.26	15.06	90.0
30.0	20.98	92.0	16.83	16.51	91.0	15.38	15.18	91.0
30.0	21.14	93.0	16.95	16.63	92.0	15.50	15.30	92.0
30.0	21.30	94.0	17.07	16.75	93.0	15.62	15.42	93.0
30.0	21.46	95.0	17.19	16.87	94.0	15.74	15.54	94.0
30.0	21.62	96.0	17.31	16.99	95.0	15.86	15.66	95.0
30.0	21.78	97.0	17.43	17.11	96.0	15.98	15.78	96.0
30.0	21.94	98.0	17.55	17.23	97.0	16.10	15.90	97.0
30.0	22.10	99.0	17.67	17.35	98.0	16.22	16.02	98.0
30.0	22.26	100.0	17.79	17.47	99.0	16.34	16.14	99.0
30.0	22.42	101.0	17.91	17.59	100.0	16.46	16.26	100.0
30.0	22.58	102.0	18.03	17.71				
30.0	22.74	103.0	18.15	17.83				
30.0	22.90	104.0	18.27	17.95				
30.0	23.06	105.0	18.39	18.07				
30.0	23.22	106.0	18.51	18.19				
30.0	23.38	107.0	18.63	18.31				
30.0	23.54	108.0	18.75	18.43				
30.0	23.70	109.0	18.87	18.55				
30.0	23.86	110.0	18.99	18.67				
30.0	24.02	111.0	19.11	18.79				
30.0	24.18	112.0	19.23	18.91				
30.0	24.34	113.0	19.35	19.03				
30.0	24.50	114.0	19.47	19.15				
30.0	24.66	115.0	19.59	19.27				
30.0	24.82	116.0	19.71	19.39				
30.0	24.98	117.0	19.83	19.51				
30.0	25.14	118.0	19.95	19.63				
30.0	25.30	119.0	20.07	19.75				
30.0	25.46	120.0	20.19	19.87				
30.0	25.62	121.0	20.31	19.99				
30.0	25.78	122.0	20.43	20.11				
30.0	25.94	123.0	20.55	20.23				
30.0	26.10	124.0	20.67	20.35				
30.0	26.26	125.0	20.79	20.47				
30.0	26.42	126.0	20.91	20.59				
30.0	26.58	127.0	21.03	20.71				
30.0	26.74	128.0	21.15	20.83				
30.0	26.90	129.0	21.27	20.95				
30.0	27.06	130.0	21.39	21.07				
30.0	27.22	131.0	21.51	21.19				
30.0	27.38	132.0	21.63	21.31				
30.0	27.54	133.0	21.75	21.43				
30.0	27.70	134.0	21.87	21.55				
30.0	27.86	135.0	21.99	21.67				
30.0	28.02	136.0	22.11	21.79				
30.0	28.18	137.0	22.23	21.91				
30.0	28.34	138.0	22.35	22.03				
30.0	28.50	139.0	22.47	22.15				
30.0	28.66	140.0	22.59	22.27				
30.0	28.82	141.0	22.71	22.39				
30.0	28.98	142.0	22.83	22.51				
30.0	29.14	143.0	22.95	22.63				
30.0	29.30	144.0	23.07	22.75				
30.0	29.46	145.0	23.19	22.87				
30.0	29.62	146.0	23.31	22.99				
30.0	29.78	147.0	23.43	23.11				
30.0	29.94	148.0	23.55	23.23				
30.0	30.10	149.0	23.67	23.35				
30.0	30.26	150.0	23.79	23.47				
30.0	30.42	151.0	23.91	23.59				
30.0	30.58	152.0	24.03	23.71				
30.0	30.74	153.0	24.15	23.83				
30.0	30.90	154.0	24.27	23.95				
30.0	31.06	155.0	24.39	24.07				
30.0	31.22	156.0	24.51	24.19				
30.0	31.38	157.0	24.63	24.31				
30.0	31.54	158.0	24.75	24.43				
30.0	31.70	159.0	24.87	24.55				
30.0	31.86	160.0	24.99	24.67				
30.0	32.02	161.0	25.11	24.79				
30.0	32.18	162.0	25.23	24.91				
30.0	32.34	163.0	25.35	25.03				
30.0	32.50	164.0	25.47	25.15				
30.0	32.66	165.0	25.59	25.27				
30.0	32.82	166.0	25.71	25.39				
30.0	32.98	167.0	25.83	25.51				
30.0	33.14	168.0	25.95	25.63				
30.0	33.30	169.0	26.07	25.75				
30.0	33.46	170.0	26.19	25.87				









TABLE 7-2. RAW DATA - LARGE FLUME - ROUGH BOUNDARIES (continued) P. 7

(Two and Three Dimensional Semicircular Model Tests)

Run No. 10-1	Run No. 10-2	Run No. 10-3	Run No. 10-4	Run No. 10-5	Run No. 10-6	Run No. 10-7	Run No. 10-8	Run No. 10-9
Q - 5.35 cfs	Q - 5.35 cfs	Q - 5.35 cfs	Q - 5.35 cfs	Q - 5.35 cfs	Q - 5.35 cfs	Q - 5.35 cfs	Q - 5.35 cfs	Q - 5.35 cfs
M - b/B = 0.300	M - b/B = 0.311	M - b/B = 0.311	M - b/B = 0.471	M - b/B = 0.500	M - b/B = 0.500	M - b/B = 0.693	M - b/B = 0.700	M - b/B = 0.700
L/b = 0.0	L/b = 0.5	L/b = 1.0	L/b = 0.0	L/b = 0.5	L/b = 1.0	L/b = 0.0	L/b = 0.5	L/b = 1.0
Slope = 0.00408	Slope = 0.00408	Slope = 0.00408	Slope = 0.00408	Slope = 0.00408	Slope = 0.00408	Slope = 0.00408	Slope = 0.00408	Slope = 0.00408
Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F
Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00
Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)
Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)
20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
11.42	9.63	26.5	7.71	7.02	7.47	6.20	6.19	6.70
11.67	24.0	10.07	24.0	24.0	24.0	24.0	24.0	24.0
26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0
11.35	10.36	11.64	8.16	7.50	7.98	6.76	6.47	6.84
26.5	11.95	29.0	26.5	26.5	26.5	26.5	26.5	26.5
27.5	27.5	27.5	8.41	7.69	27.5	27.5	27.5	27.5
12.05	10.44	29.5	26.5	7.63	8.13	6.56	6.55	6.85
28.0	11.38	31.58	26.0	27.5	27.5	27.5	27.5	27.5
12.11	28.0	35.78	8.42	7.72	8.20	6.63	6.62	6.82
29.0	10.51	31.58	26.0	28.0	28.0	28.0	28.0	28.0
12.09	10.48	29.0	29.0	7.66	29.0	29.0	29.0	29.0
29.5	29.5	31.2*	8.16	34.18	8.16	33.00	32.16	34.39
31.0	31.0	31.0	32.70	4.42*	34.07	4.19*	4.70*	4.70*
32.0	32.0	32.0						
32.5	32.5	32.5						
34.5	34.5	34.5						
35.0	35.0	35.0						
35.5	35.5	35.5						
37.0	37.0	37.0						

Run No. 10-10	Run No. 10-11	Run No. 10-12	Run No. 11-1	Run No. 11-2	Run No. 11-3	Run No. 11-4	Run No. 11-5	Run No. 11-6
Q - 5.35 cfs	Q - 5.35 cfs	Q - 5.35 cfs	Q - 7.49 cfs	Q - 7.49 cfs	Q - 7.49 cfs	Q - 7.49 cfs	Q - 7.49 cfs	Q - 7.49 cfs
M - b/B = 0.889	M - b/B = 0.900	M - b/B = 0.900	M - b/B = 0.300	M - b/B = 0.311	M - b/B = 0.311	M - b/B = 0.311	M - b/B = 0.500	M - b/B = 0.500
L/b = 0.0	L/b = 0.5	L/b = 1.0	L/b = 0.0	L/b = 0.5	L/b = 1.0	L/b = 0.0	L/b = 0.5	L/b = 1.0
Slope = 0.00408	Slope = 0.00408	Slope = 0.00408	Slope = 0.00334	Slope = 0.00334	Slope = 0.00334	Slope = 0.00334	Slope = 0.00334	Slope = 0.00334
Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F	Temp. 70°F
Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00
Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)
Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)
20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
5.59	5.67	5.71	18.97	18.48	19.38	11.89	11.89	12.66
26.0	26.0	26.0	24.0	24.0	27.0	24.0	24.0	26.5
26.5	26.5	26.5	19.61	18.65	27.5	24.0	24.0	26.5
27.0	27.0	27.0	26.0	26.5	28.5	26.0	26.0	26.5
27.5	27.5	27.5	26.0	26.5	28.5	26.0	26.0	26.5
28.0	28.0	28.0	26.0	26.5	28.5	26.0	26.0	26.5
28.5	28.5	28.5	26.0	26.5	28.5	26.0	26.0	26.5
29.0	29.0	29.0	26.0	26.5	28.5	26.0	26.0	26.5
29.5	29.5	29.5	26.0	26.5	28.5	26.0	26.0	26.5
30.0	30.0	30.0	26.0	26.5	28.5	26.0	26.0	26.5
30.5	30.5	30.5	26.0	26.5	28.5	26.0	26.0	26.5
31.0	31.0	31.0	26.0	26.5	28.5	26.0	26.0	26.5
31.5	31.5	31.5	26.0	26.5	28.5	26.0	26.0	26.5
32.0	32.0	32.0	26.0	26.5	28.5	26.0	26.0	26.5
32.5	32.5	32.5	26.0	26.5	28.5	26.0	26.0	26.5
33.0	33.0	33.0	26.0	26.5	28.5	26.0	26.0	26.5
33.5	33.5	33.5	26.0	26.5	28.5	26.0	26.0	26.5
34.0	34.0	34.0	26.0	26.5	28.5	26.0	26.0	26.5
34.5	34.5	34.5	26.0	26.5	28.5	26.0	26.0	26.5
35.0	35.0	35.0	26.0	26.5	28.5	26.0	26.0	26.5
35.5	35.5	35.5	26.0	26.5	28.5	26.0	26.0	26.5
36.0	36.0	36.0	26.0	26.5	28.5	26.0	26.0	26.5
36.5	36.5	36.5	26.0	26.5	28.5	26.0	26.0	26.5
37.0	37.0	37.0	26.0	26.5	28.5	26.0	26.0	26.5



TABLE 7-2-1. RAW DATA - LAME FLUME - REXX BOUNDARIES (continued) P. 8

(Two and Three Dimensional Semicircular Model Tests)

Run No. 11-7	Run No. 11-8	Run No. 11-9	Run No. 11-10	Run No. 11-11	Run No. 11-12	Run No. 12-1	Run No. 12-2	Run No. 12-3
Q - 2 cfs	Q - 2 cfs	Q - 2 cfs	Q - 7.49 cfs	Q - 7.49 cfs	Q - 7.49 cfs	Q - 3 cfs	Q - 3 cfs	Q - 3 cfs
$Y_n = 7.49$ cm.	$Y_n = 7.49$ cm.	$Y_n = 7.49$ cm.	$Y_n = 7.49$ cm.	$Y_n = 7.49$ cm.	$Y_n = 7.49$ cm.	$Y_n = 8.70$ cm.	$Y_n = 8.70$ cm.	$Y_n = 8.70$ cm.
$H = b/B = 0.693$	$H = b/B = 0.700$	$H = b/B = 0.700$	$H = b/B = 0.889$	$H = b/B = 0.900$	$H = b/B = 0.900$	$H = b/B = 0.900$	$H = b/B = 0.911$	$H = b/B = 0.911$
$L/b = 0.0$	$L/b = 0.5$	$L/b = 1.0$	$L/b = 0.0$	$L/b = 0.5$	$L/b = 1.0$	$L/b = 0.0$	$L/b = 0.5$	$L/b = 0.5$
Slope = 0.00748	Slope = 0.00534	Slope = 0.00534	Slope = 0.00534	Slope = 0.00534	Slope = 0.00534	Slope = 0.00748	Slope = 0.00748	Slope = 0.00748
Temp. = 72F	Temp. = 72F	Temp. = 72F	Temp. = 72F	Temp. = 72F	Temp. = 72F	Temp. = 72F	Temp. = 72F	Temp. = 72F
Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00	Model Sta. = 30.00
Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)	Cent. Sta. (ft.)
Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)	Depth (cm.)
20.0	9.01	10.01	20.0	24.0	24.0	25.0	25.0	25.0
25.0	9.43	10.12	24.0	25.0	25.0	25.0	25.0	25.0
30.0	9.85	10.23	24.0	26.0	26.0	26.0	26.0	26.0
35.0	10.27	10.34	24.0	27.0	27.0	27.0	27.0	27.0
40.0	10.69	10.40	24.0	28.0	28.0	28.0	28.0	28.0
45.0	11.11	10.51	24.0	29.0	29.0	29.0	29.0	29.0
50.0	11.53	10.62	24.0	30.0	30.0	30.0	30.0	30.0
55.0	11.95	10.73	24.0	31.0	31.0	31.0	31.0	31.0
60.0	12.37	10.84	24.0	32.0	32.0	32.0	32.0	32.0
65.0	12.79	10.95	24.0	33.0	33.0	33.0	33.0	33.0
70.0	13.21	11.06	24.0	34.0	34.0	34.0	34.0	34.0
75.0	13.63	11.17	24.0	35.0	35.0	35.0	35.0	35.0
80.0	14.05	11.28	24.0	36.0	36.0	36.0	36.0	36.0
85.0	14.47	11.39	24.0	37.0	37.0	37.0	37.0	37.0
90.0	14.89	11.50	24.0	38.0	38.0	38.0	38.0	38.0
95.0	15.31	11.61	24.0	39.0	39.0	39.0	39.0	39.0
100.0	15.73	11.72	24.0	40.0	40.0	40.0	40.0	40.0
105.0	16.15	11.83	24.0	41.0	41.0	41.0	41.0	41.0
110.0	16.57	11.94	24.0	42.0	42.0	42.0	42.0	42.0
115.0	16.99	12.05	24.0	43.0	43.0	43.0	43.0	43.0
120.0	17.41	12.16	24.0	44.0	44.0	44.0	44.0	44.0
125.0	17.83	12.27	24.0	45.0	45.0	45.0	45.0	45.0
130.0	18.25	12.38	24.0	46.0	46.0	46.0	46.0	46.0
135.0	18.67	12.49	24.0	47.0	47.0	47.0	47.0	47.0
140.0	19.09	12.60	24.0	48.0	48.0	48.0	48.0	48.0
145.0	19.51	12.71	24.0	49.0	49.0	49.0	49.0	49.0
150.0	19.93	12.82	24.0	50.0	50.0	50.0	50.0	50.0
155.0	20.35	12.93	24.0	51.0	51.0	51.0	51.0	51.0
160.0	20.77	13.04	24.0	52.0	52.0	52.0	52.0	52.0
165.0	21.19	13.15	24.0	53.0	53.0	53.0	53.0	53.0
170.0	21.61	13.26	24.0	54.0	54.0	54.0	54.0	54.0
175.0	22.03	13.37	24.0	55.0	55.0	55.0	55.0	55.0
180.0	22.45	13.48	24.0	56.0	56.0	56.0	56.0	56.0
185.0	22.87	13.59	24.0	57.0	57.0	57.0	57.0	57.0
190.0	23.29	13.70	24.0	58.0	58.0	58.0	58.0	58.0
195.0	23.71	13.81	24.0	59.0	59.0	59.0	59.0	59.0
200.0	24.13	13.92	24.0	60.0	60.0	60.0	60.0	60.0
205.0	24.55	14.03	24.0	61.0	61.0	61.0	61.0	61.0
210.0	24.97	14.14	24.0	62.0	62.0	62.0	62.0	62.0
215.0	25.39	14.25	24.0	63.0	63.0	63.0	63.0	63.0
220.0	25.81	14.36	24.0	64.0	64.0	64.0	64.0	64.0
225.0	26.23	14.47	24.0	65.0	65.0	65.0	65.0	65.0
230.0	26.65	14.58	24.0	66.0	66.0	66.0	66.0	66.0
235.0	27.07	14.69	24.0	67.0	67.0	67.0	67.0	67.0
240.0	27.49	14.80	24.0	68.0	68.0	68.0	68.0	68.0
245.0	27.91	14.91	24.0	69.0	69.0	69.0	69.0	69.0
250.0	28.33	15.02	24.0	70.0	70.0	70.0	70.0	70.0
255.0	28.75	15.13	24.0	71.0	71.0	71.0	71.0	71.0
260.0	29.17	15.24	24.0	72.0	72.0	72.0	72.0	72.0
265.0	29.59	15.35	24.0	73.0	73.0	73.0	73.0	73.0
270.0	30.01	15.46	24.0	74.0	74.0	74.0	74.0	74.0
275.0	30.43	15.57	24.0	75.0	75.0	75.0	75.0	75.0
280.0	30.85	15.68	24.0	76.0	76.0	76.0	76.0	76.0
285.0	31.27	15.79	24.0	77.0	77.0	77.0	77.0	77.0
290.0	31.69	15.90	24.0	78.0	78.0	78.0	78.0	78.0
295.0	32.11	16.01	24.0	79.0	79.0	79.0	79.0	79.0
300.0	32.53	16.12	24.0	80.0	80.0	80.0	80.0	80.0
305.0	32.95	16.23	24.0	81.0	81.0	81.0	81.0	81.0
310.0	33.37	16.34	24.0	82.0	82.0	82.0	82.0	82.0
315.0	33.79	16.45	24.0	83.0	83.0	83.0	83.0	83.0
320.0	34.21	16.56	24.0	84.0	84.0	84.0	84.0	84.0
325.0	34.63	16.67	24.0	85.0	85.0	85.0	85.0	85.0
330.0	35.05	16.78	24.0	86.0	86.0	86.0	86.0	86.0
335.0	35.47	16.89	24.0	87.0	87.0	87.0	87.0	87.0
340.0	35.89	17.00	24.0	88.0	88.0	88.0	88.0	88.0
345.0	36.31	17.11	24.0	89.0	89.0	89.0	89.0	89.0
350.0	36.73	17.22	24.0	90.0	90.0	90.0	90.0	90.0
355.0	37.15	17.33	24.0	91.0	91.0	91.0	91.0	91.0
360.0	37.57	17.44	24.0	92.0	92.0	92.0	92.0	92.0
365.0	37.99	17.55	24.0	93.0	93.0	93.0	93.0	93.0
370.0	38.41	17.66	24.0	94.0	94.0	94.0	94.0	94.0
375.0	38.83	17.77	24.0	95.0	95.0	95.0	95.0	95.0
380.0	39.25	17.88	24.0	96.0	96.0	96.0	96.0	96.0
385.0	39.67	17.99	24.0	97.0	97.0	97.0	97.0	97.0
390.0	40.09	18.10	24.0	98.0	98.0	98.0	98.0	98.0
395.0	40.51	18.21	24.0	99.0	99.0	99.0	99.0	99.0
400.0	40.93	18.32	24.0	100.0	100.0	100.0	100.0	100.0
405.0	41.35	18.43	24.0					
410.0	41.77	18.54	24.0					
415.0	42.19	18.65	24.0					
420.0	42.61	18.76	24.0					
425.0	43.03	18.87	24.0					
430.0	43.45	18.98	24.0					
435.0	43.87	19.09	24.0					
440.0	44.29	19.20	24.0					
445.0	44.71	19.31	24.0					
450.0	45.13	19.42	24.0					
455.0	45.55	19.53	24.0					
460.0	45.97	19.64	24.0					
465.0	46.39	19.75	24.0					
470.0	46.81	19.86	24.0					
475.0	47.23	19.97	24.0					
480.0	47.65	20.08	24.0					
485.0	48.07	20.19	24.0					
490.0	48.49	20.30	24.0					
495.0	48.91	20.41	24.0					
500.0	49.33	20.52	24.0					
505.0	49.75	20.63	24.0					
510.0	50.17	20.74	24.0					
515.0	50.59	20.85	24.0					
520.0	51.01	20.96	24.0					
525.0	51.43	21.07	24.0					
530.0	51.85	21.18	24.0					
535.0	52.27	21.29	24.0					
540.0	52.69	21.40	24.0					
545.0	53.11	21.51	24.0					
550.0	53.53	21.62	24.0					
555.0	53.95	21.73	24.0					
560.0	54.37	21.84	24.0					
565.0	54.79	21.95	24.0					
570.0	55.21	22.06	24.0					
575.0	55.63	22.17	24.0					
580.0	56.05	22.28	24.0					
585.0	56.47	22.39	24.0					
590.0	56.89	22.50	24.0					
595.0	57.31	22.61	24.0					
600.0	57.73	22.72	24.0					
605.0	58.15	22.83	24.0					
610.0	58.57	22.94	24.0					
615.0	58.99	23.05	24.0					
620.0	59.41	23.16	24.0					
625.0	59.83	23.27	24.0					
630.0	60.25	23.38	24.0					
635.0	60.67	23.49	24.0					
640.0	61.09	23.60	24.0					
645.0	61.51	23.71	24.0					
650.0	61.93	23.82	24.0					
655.0	62.35	23.93	24.0					
660.0	62.77	24.04	24.0					
665.0	63.19	24.15	24.0					
670.0	63.61	24.26	24.0					
675.0	64.03	24.37	24.0					
680.0	64.45	24.48	24.0					
685.0	64.87	24.59	24.0					
690.0	65.29	24.70	24.0					
695.0	65.71	24.81	24.0					
700.0	66.13	24.92	24.0					
705.0	66.55	25.03	24.0					
710.0								









TABLE 7-2-1 RAW DATA - LARGE FLUME - ROUGH BOUNDARIES (continued) P. 10  
(Two and Three Dimensional Semicircular Model Tests)

Run No. 14-7				Run No. 14-8				Run No. 14-9				Run No. 14-10				Run No. 14-11				Run No. 14-12			
Q - 2 cfs				Q - 2 cfs				Q - 2 cfs				Q - 2 cfs				Q - 2 cfs				Q - 2 cfs			
$Y_n - 6.02$ cm.				$Y_n - 6.02$ cm.				$Y_n - 6.02$ cm.				$Y_n - 6.02$ cm.				$Y_n - 6.02$ cm.				$Y_n - 6.02$ cm.			
$M - b/B - 0.693$				$M - b/B - 0.700$				$M - b/B - 0.700$				$M - b/B - 0.889$				$M - b/B - 0.900$				$M - b/B - 0.900$			
$L/b - 0.0$				$L/b - 0.5$				$L/b - 1.0$				$L/b - 0.0$				$L/b - 0.5$				$L/b - 1.0$			
Slope - 0.0123				Slope - 0.0123				Slope - 0.0123				Slope - 0.0123				Slope - 0.0123				Slope - 0.0123			
Temp. - 74F				Temp. - 76F				Temp. - 76F				Temp. - 74F				Temp. - 74F				Temp. - 74F			
Model Sta. - 30.00				Model Sta. - 30.00				Model Sta. - 30.00				Model Sta. - 30.00				Model Sta. - 30.00				Model Sta. - 30.00			
Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)	Cent. Sta. (ft.)	Depth (cm.)
28.82	9.01****	28.20	9.13****	28.73	9.40****	27.31	6.69****	29.34	6.95****	29.38	7.03****	29.38	7.03****	29.38	7.03****	29.38	7.03****	29.38	7.03****	29.38	7.03****	29.38	7.03****
33.10	4.56*	34.59	4.23*	36.10	4.42*	32.37	5.53*	32.86	5.13*	36.50	5.40*	32.86	5.13*	36.50	5.40*	32.86	5.13*	36.50	5.40*	32.86	5.13*	36.50	5.40*

## Notes:

- \* Only the minimum depth was measured on the downstream side of the bridge model.
- \*\* Runs for which no measurements were taken on the downstream side of the bridge model.
- \*\*\* Runs for which a detail of the regain curve is given in Table VIII.
- \*\*\*\* Runs for which only the maximum and minimum depths were read and recorded. No other measurements were taken.



GEOMETRY I<sub>0</sub> AND I<sub>b</sub>

TABLE 7-2-2 CALCULATIONS FOR THE LARGE FLIPS ROUGH BOUNDARY MODEL TESTS

P. 1

Measured Data										Calculated Data													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
un bo.	$l/b$	$M$	$S_n$	$Q$	$y_n$	$y_1$	$y_2$	$y_3$	$y \times 10^5$	$y_1$ Sta.	$y_2$ Sta.	$y_3$ Sta.	$R$	$F_n$	$R_0$	$f$	$M^*$	$C_d$	$x_1/y_n$	$(F_n/\rho y^2)^{1/3}$	$h^*$	$y_1 - y_2$	$l_1 - l_2$
1-1	0.0	0.300	0.000030	1.0	24.52	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-2	0.0	0.311	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-3	1.0	0.491	-	-	24.54	-	-	-	1.164	26.50	-	-	-	-	-	-	-	-	-	-	-	-	-
1-4	0.5	0.500	-	-	24.67	-	-	-	1.091	26.50	-	-	-	-	-	-	-	-	-	-	-	-	-
1-5	0.5	0.500	-	-	24.67	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-6	0.0	0.693	-	-	24.58	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-7	0.0	0.700	-	-	24.59	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-8	0.5	0.700	-	-	24.59	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-9	1.0	0.700	-	-	24.58	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-10	0.5	0.900	-	-	24.60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1-11	1.0	0.900	-	-	24.60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-1	0.0	0.300	0.000131	2.0	24.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-2	0.0	0.311	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-3	1.0	0.491	-	-	24.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-4	0.0	0.491	-	-	24.90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-5	0.5	0.600	-	-	24.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-6	0.5	0.600	-	-	24.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-7	0.0	0.693	-	-	24.07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-8	0.0	0.700	-	-	24.07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-9	0.5	0.700	-	-	24.07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-10	1.0	0.700	-	-	24.07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-11	0.0	0.900	-	-	24.07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2-12	1.0	0.900	-	-	24.07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-1	0.0	0.300	0.000089	3.0	24.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-2	0.0	0.311	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-3	1.0	0.491	-	-	24.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-4	0.0	0.491	-	-	24.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-5	0.5	0.600	-	-	25.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-6	0.5	0.600	-	-	25.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-7	0.0	0.693	-	-	24.46	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-8	0.5	0.700	-	-	24.32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-9	0.5	0.700	-	-	24.32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-10	0.0	0.900	-	-	24.13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-11	0.5	0.900	-	-	24.13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3-12	1.0	0.900	-	-	24.13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-1	0.0	0.300	0.000084	1.0	9.64	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-2	0.0	0.311	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-3	0.5	0.491	-	-	10.66	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-4	0.5	0.491	-	-	10.66	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-5	1.0	0.600	-	-	10.60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-6	0.5	0.693	-	-	9.94	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-7	0.5	0.700	-	-	9.89	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-8	0.5	0.700	-	-	9.66	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-9	0.0	0.900	-	-	9.69	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-10	0.5	0.900	-	-	9.69	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-11	1.0	0.900	-	-	9.69	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-12	0.0	0.300	0.000070	2.0	13.28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-13	0.0	0.311	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-14	0.5	0.491	-	-	18.95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-15	0.5	0.491	-	-	18.95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-16	1.0	0.600	-	-	13.26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-17	0.5	0.700	-	-	11.87	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-18	0.5	0.700	-	-	11.87	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-19	1.0	0.700	-	-	13.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-20	0.0	0.900	-	-	13.76	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-21	0.5	0.900	-	-	13.76	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-22	1.0	0.900	-	-	13.77	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-23	0.0	0.300	0.000070	2.0	13.28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-24	0.0	0.311	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-25	0.5	0.491	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-26	0.5	0.491	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-27	0.5	0.600	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-28	0.5	0.600	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-29	0.5	0.700	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-30	0.5	0.700	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-31	0.5	0.700	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-32	0.5	0.700	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-33	0.5	0.700	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4-34	0.5	0.700	-	-	13.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-









TABLE 7-2.2 CALCULATIONS FOR THE LARGE FLUME RAUGH BOUNDARY MODEL TESTS (continued) P. 3

un. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Calculated Data							
																		$H'$	$C_d$	$y_1/n$	$(y_1/n)^{1/3}$	$h_1^*$	$y_1 - y_3$	$h_1 - y_3$	$h_1 - y_3$
11-1	11-1	0.5	0.300	0.00534	2.0	7.49	20.19	3.42	0.944	28.50	31.25	30.00	0.2237	0.5775	38.616	0.1158	0.2945	0.4906	2.696	1.570	0.4167	0.5409	1.50	4.75	
11-2	11-2	0.5	0.311	"	"	"	19.10	3.71	0.917	28.50	31.25	30.00	"	"	"	39.753	"	0.3077	0.5029	2.654	1.570	0.3809	0.5049	2.00	5.60
11-3	11-3	1.0	0.311	"	"	"	15.58	2.68	0.947	28.50	31.25	30.00	"	"	"	39.753	"	0.3077	0.5029	2.654	1.570	0.3809	0.5049	2.00	5.60
11-4	11-4	0.0	0.693	"	"	"	12.50	4.11	0.917	27.50	33.60	30.00	"	"	"	38.616	"	0.4968	0.5215	1.718	1.122	0.1634	0.2753	2.50	6.10
11-5	11-5	0.5	0.500	"	"	"	12.50	4.11	0.917	28.00	32.65	30.00	"	"	"	38.616	"	0.4968	0.5215	1.718	1.122	0.1634	0.2753	2.50	6.10
11-6	11-6	1.0	0.693	"	"	"	9.48	5.96	0.917	28.00	33.21	30.00	"	"	"	38.616	"	0.6507	0.6519	1.306	0.889	0.0751	0.1158	2.00	5.21
11-7	11-7	0.5	0.700	"	"	"	10.20	5.45	0.944	28.00	33.21	30.00	"	"	"	38.616	"	0.6507	0.6519	1.306	0.889	0.0751	0.1158	2.00	5.21
11-8	11-8	0.0	0.899	"	"	"	8.02	6.33	0.944	28.00	32.92	30.00	"	"	"	38.616	"	0.8872	0.8883	1.072	0.752	0.0174	0.0534	2.00	4.00
11-9	11-9	0.5	0.899	"	"	"	8.02	6.33	0.944	28.00	32.92	30.00	"	"	"	38.616	"	0.8872	0.8883	1.072	0.752	0.0174	0.0534	2.00	4.00
11-10	11-10	0.5	0.900	"	"	"	8.02	6.33	0.944	28.00	32.92	30.00	"	"	"	38.616	"	0.8872	0.8883	1.072	0.752	0.0174	0.0534	2.00	4.00
11-11	11-11	0.5	0.900	"	"	"	8.02	6.33	0.944	28.00	32.92	30.00	"	"	"	38.616	"	0.8872	0.8883	1.072	0.752	0.0174	0.0534	2.00	4.00
11-12	11-12	1.0	0.900	0.00748	3.0	8.70	"	7.23	0.944	28.50	31.25	30.00	"	"	"	38.616	"	0.8982	0.8993	1.072	0.752	0.0174	0.0534	2.00	4.00
12-1	12-1	0.5	0.311	"	"	"	16.70	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"
12-2	12-2	0.5	0.311	"	"	"	16.70	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"
12-3	12-3	0.5	0.311	"	"	"	16.70	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"
12-4	12-4	0.0	0.691	"	"	"	17.05	4.79	1.033	28.00	33.59	30.00	0.5562	0.6943	52.178	0.1114	0.4906	0.5576	1.484	1.261	0.2740	0.4439	2.00	5.59	
12-5	12-5	0.5	0.500	"	"	"	17.05	4.13	1.059	28.50	35.05	30.00	"	"	"	50.577	"	0.4956	0.5029	1.484	1.261	0.2740	0.4439	2.00	5.59
12-6	12-6	0.5	0.500	"	"	"	17.05	4.13	1.059	28.50	35.05	30.00	"	"	"	50.577	"	0.4956	0.5029	1.484	1.261	0.2740	0.4439	2.00	5.59
12-7	12-7	0.0	0.693	"	"	"	12.60	5.95	1.059	28.50	31.25	30.00	"	"	"	51.530	"	0.6898	0.5780	1.484	1.004	0.1280	0.2310	1.50	4.86
12-8	12-8	0.5	0.700	"	"	"	12.60	5.95	1.059	28.00	31.25	30.00	"	"	"	51.530	"	0.6898	0.5780	1.484	1.004	0.1280	0.2310	1.50	4.86
12-9	12-9	0.0	0.899	"	"	"	12.87	6.00	1.046	28.00	31.25	30.00	"	"	"	51.530	"	0.8865	0.6807	1.577	0.842	0.1368	0.2254	2.00	7.48
12-10	12-10	0.5	0.900	"	"	"	9.54	8.03	1.033	27.50	31.53	30.00	"	"	"	52.178	"	0.8865	0.6807	1.577	0.842	0.1368	0.2254	2.00	7.48
12-11	12-11	0.5	0.900	"	"	"	9.72	7.71	1.033	27.50	31.53	30.00	"	"	"	52.178	"	0.8865	0.6807	1.577	0.842	0.1368	0.2254	2.00	7.48
12-12	12-12	1.0	0.900	"	"	"	9.82	7.92	1.033	27.50	31.53	30.00	"	"	"	52.178	"	0.8865	0.6807	1.577	0.842	0.1368	0.2254	2.00	7.48
13-1	13-1	0.0	0.311	"	"	"	11.07	2.52	0.917	28.62	33.28	30.00	"	"	"	20.711	"	0.8976	0.6400	1.259	1.784	0.2539	0.3064	1.00	4.08
13-2	13-2	0.0	0.311	"	"	"	11.07	2.52	0.917	28.62	33.28	30.00	"	"	"	20.711	"	0.8976	0.6400	1.259	1.784	0.2539	0.3064	1.00	4.08
13-3	13-3	1.0	0.311	"	"	"	11.08	2.66	0.917	28.60	33.50	30.00	"	"	"	20.711	"	0.8976	0.6400	1.259	1.784	0.2539	0.3064	1.00	4.08
13-4	13-4	0.0	0.491	"	"	"	7.28	3.15	0.917	28.50	33.65	30.00	"	"	"	20.711	"	0.8976	0.6400	1.259	1.784	0.2539	0.3064	1.00	4.08
13-5	13-5	0.5	0.500	"	"	"	7.50	3.09	0.917	29.00	34.63	30.00	"	"	"	20.711	"	0.8976	0.6400	1.259	1.784	0.2539	0.3064	1.00	4.08
13-6	13-6	0.5	0.500	"	"	"	7.50	3.09	0.917	29.00	34.63	30.00	"	"	"	20.711	"	0.8976	0.6400	1.259	1.784	0.2539	0.3064	1.00	4.08
13-7	13-7	0.0	0.693	"	"	"	5.80	3.29	0.944	27.50	33.51	30.00	"	"	"	20.711	"	0.6973	0.5845	1.446	1.017	0.0951	0.1447	1.50	5.63
13-8	13-8	0.5	0.700	"	"	"	6.05	3.55	0.917	28.00	35.08	30.00	"	"	"	20.711	"	0.6973	0.5845	1.446	1.017	0.0951	0.1447	1.50	5.63
13-9	13-9	0.0	0.899	"	"	"	4.55	3.84	0.917	27.43	32.46	30.00	"	"	"	20.711	"	0.8885	0.6875	1.112	0.861	0.0341	0.0523	2.17	5.03
13-10	13-10	0.0	0.899	"	"	"	4.55	3.84	0.917	27.43	32.46	30.00	"	"	"	20.711	"	0.8885	0.6875	1.112	0.861	0.0341	0.0523	2.17	5.03
13-11	13-11	0.5	0.900	"	"	"	4.98	3.97	0.917	28.10	34.65	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
13-12	13-12	1.0	0.900	0.03230	2.0	6.02	39.83	3.48	1.020	29.00	34.05	30.00	0.1830	0.8612	20.711	0.1685	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03	
14-1	14-1	0.0	0.300	"	"	"	16.81	3.31	1.007	28.90	34.55	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-2	14-2	0.5	0.311	"	"	"	17.60	3.25	1.007	28.92	35.16	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-3	14-3	1.0	0.311	"	"	"	17.60	3.25	1.007	28.92	35.16	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-4	14-4	0.0	0.691	"	"	"	12.49	3.69	1.007	28.86	34.06	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-5	14-5	0.5	0.600	"	"	"	11.07	3.90	1.007	29.00	35.10	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-6	14-6	0.0	0.693	"	"	"	9.01	4.56	1.007	28.42	33.30	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-7	14-7	0.0	0.693	"	"	"	9.13	4.73	0.970	28.70	34.10	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-8	14-8	0.5	0.700	"	"	"	9.40	4.93	1.007	27.50	32.57	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-9	14-9	0.0	0.899	"	"	"	6.69	5.13	1.007	27.50	32.57	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-10	14-10	0.0	0.899	"	"	"	6.69	5.13	1.007	27.50	32.57	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-11	14-11	0.5	0.900	"	"	"	7.03	5.40	0.970	29.38	36.50	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03
14-12	14-12	1.0	0.900	"	"	"	7.03	5.40	0.970	29.38	36.50	30.00	"	"	"	20.711	"	0.8995	0.6975	1.112	0.861	0.0341	0.0523	2.17	5.03

\* Test runs where the crown of the arch was submerged.





## Geometry Ia

TABLE 7-2-3- SURFACE TOPOGRAPHY &amp; REGAIN CURVE DATA

## A) Surface Topography

Run No. 4-4;  $Q = 1$  cfs;  $S = 0.000584$ ;  $y_n = 9.72$  cm.;  $M = 0.491$ ; $L/b = 0$ ; Model Station = 29.90 ft.:

Centerline Station	Station Left	Depths (cm.)	
		Centerline	Left
15.00		10.58	
	1.00		10.57
	2.00		10.54
16.00		10.56	
17.00		10.58	
18.00		10.61	
	1.00		10.61
	2.00		10.62
19.00		10.63	
20.00		10.63	
	1.00		10.61
	2.00		10.59
21.00		10.62	
22.00		10.63	
	1.00		10.61
	2.00		10.58
23.00		10.63	
24.00		10.63	
	1.00		10.63
	2.00		10.61
25.00		10.64	
26.00		10.65	
	1.00		10.66
	2.00		10.63
26.50		10.65	
27.50		10.64	
	1.00		10.64
	2.00		10.65
28.00		10.61	
	1.00		10.65
	2.00		10.66
28.50		10.56	
	1.00		10.60
	2.00		10.66
29.00		10.47	
	0.50		10.51
	1.00		10.56
	1.50		10.64
	2.00		10.72



## 7-2-3 (CONTO.)

Centerline Station	Station Left	Depths (cm.)	
		Centerline	Left
29.25		10.39	
	0.50		10.43
	1.00		10.50
	1.50		10.65
29.50	2.00	10.21	10.71
	0.50		10.25
	1.00		10.34
	1.50		10.75
	2.00		10.72
29.79	2.32	10.09	10.70
	0.50		10.09
	0.75		10.07
	1.00		10.17
	1.25		10.53
	1.50		10.72
	1.75		10.76
	2.00		10.76
30.20	2.32	9.95	10.73
	0.50		9.86
	0.75		9.74
	1.00		9.55
	1.25		9.09
	1.50		9.07
30.50	2.00	9.57	9.05
	0.50		9.45
	1.00		9.17
	1.50		9.07
	2.00		9.06
31.00		9.27	
	1.00		9.13
	1.50		9.08
	2.00		9.07
31.50		9.06	
	1.00		9.07
	2.00		9.08
32.0		9.02	
	1.00		9.10
	2.00		9.07
32.50		9.05	
33.00		9.04	
	1.00		9.07
	2.00		9.13
34.00		9.15	
	2.00		9.14
35.00		9.12	



Centerline Station	Station Left	Depths (cm.)	
		Centerline	Left
36.00	2.00	9.22	
37.00		9.35	9.18
38.00		9.38	
39.00		9.40	
40.00		9.43	
41.00		9.45	
42.00		9.50	
43.00		9.53	
44.00		9.55	
45.00		9.57	
46.00		9.58	

## B) Regain Curves

Run No. 1-4;  $Q = 1$  cfs;  $y_n = 24.50$  cm.; Run No. 2-7;  $Q = 2$  cfs;  $y_n = 24.30$  cm.;  
 $S = 0.0000302$ ;  $M = 0.491$ ;  $L/b = 0$ ;  $S = 0.000131$ ;  $M = 0.693$ ;  $L/b = 0$ ;  
 Model Station = 30.00 ft.; Model Station = 30.00 ft.;

Centerline	Depth (cm.)	Centerline	Depth (cm.)
31.00	24.24	31.00	24.20
31.50	24.15	31.50	24.15
32.00	24.13	32.00	24.12
32.50	24.11	32.50	24.13
33.00	24.10	33.00	24.14
33.50	24.07	33.50	24.14
34.00	24.14	34.00	24.15
34.50	24.17	35.00	24.19
35.00	24.20	36.00	24.21
36.00	24.22	37.00	24.24
37.00	24.26	38.00	24.27
38.00	24.30	39.00	24.30
39.00	24.34	40.00	24.29
42.00	24.35	41.00	24.30
44.00	24.40		
46.00	24.44		
48.00	24.46		
50.00	24.50		
52.00	24.51		
54.00	24.50		





## Geometry Is

TABLE 7-2-4 VELOCITY MEASUREMENTS

## A) Velocity Profiles for Run No. 4-4

$Q = 1$  cfs;  $S = 0.000584$ ;  $y_n = 9.72$  cm.;  $M = 0.491$ ;  $L/b = 0$ ;  
Model Station = 30.00 ft.:

## a. Normal Depth

Centerline		1 ft. Left		2 ft. Left	
Depth	Velocity	Depth	Velocity	Depth	Velocity
ft.	fps	ft.	fps	ft.	fps
0.010	0.447	0.010	0.447	0.010	0.347
0.015	0.490	0.020	0.425	0.020	0.347
0.020	0.490	0.030	0.490	0.030	0.347
0.025	0.490	0.040	0.470	0.040	0.347
0.030	0.565	0.050	0.470	0.060	0.490
0.035	0.565	0.060	0.528	0.080	0.528
0.040	0.565	0.070	0.585	0.100	0.565
0.045	0.618	0.080	0.600	0.120	0.600
0.050	0.635	0.090	0.650	0.140	0.635
0.060	0.650	0.100	0.650	0.160	0.650
0.070	0.695	0.120	0.665	0.200	0.695
0.080	0.695	0.140	0.722	0.240	0.748
0.090	0.695	0.160	0.708	0.280	0.762
0.100	0.748	0.200	0.735		
0.120	0.762	0.240	0.748		
0.140	0.788	0.280	0.775		
0.160	0.788				
0.200	0.837				
0.240	0.837				
0.280	0.850				

## b. Maximum Depth

Centerline		1 ft. Left		2 ft. Left	
Depth	Velocity	Depth	Velocity	Depth	Velocity
ft.	fps	ft.	fps	ft.	fps
0.040	0.528	0.040	0.566	0.050	0.447
0.045	0.547	0.050	0.602	0.060	0.447
0.050	0.547	0.060	0.618	0.070	0.468
0.055	0.547	0.070	0.634	0.080	0.468
0.060	0.547	0.080	0.650	0.090	0.509
0.070	0.547	0.090	0.695	0.100	0.489
0.080	0.566	0.100	0.695	0.120	0.566
0.090	0.634	0.120	0.708	0.140	0.566
0.100	0.618	0.140	0.722	0.160	0.566
0.110	0.650	0.160	0.749	0.180	0.634
0.120	0.695	0.180	0.749	0.200	0.650



7-2-4 (CONTD.)

0.130	0.695	0.200	0.775	0.220	0.650
0.140	0.695	0.220	0.788	0.240	0.680
0.160	0.695	0.240	0.813	0.260	0.695
0.180	0.749	0.260	0.837	0.280	0.695
0.200	0.749	0.280	0.837	0.300	0.695
0.220	0.749	0.300	0.813		
0.240	0.749				
0.260	0.788				
0.280	0.800				
0.300	0.837				

## c. Vena Contracta

Centerline		0.5 ft. Left		1.0 ft. Left	
Depth	Velocity	Depth	Velocity	Depth	Velocity
ft.	fps	ft.	fps	ft.	fps
0.010	1.145	0.010	1.206	0.010	1.090
0.015	1.154	0.020	1.215	0.020	1.180
0.020	1.163	0.030	1.230	0.030	1.300
0.025	1.170	0.040	1.240	0.040	1.390
0.030	1.180	0.050	1.280	0.050	1.490
0.035	1.206	0.060	1.313	0.060	1.581
0.040	1.230	0.070	1.367	0.070	1.594
0.045	1.265	0.080	1.432	0.080	1.642
0.050	1.300	0.090	1.470	0.090	1.654
0.060	1.350	0.100	1.490	0.100	1.690
0.070	1.367	0.120	1.524	0.120	1.690
0.080	1.410	0.140	1.534	0.140	1.724
0.090	1.420	0.160	1.543	0.160	1.770
0.100	1.455	0.180	1.555	0.200	1.758
0.120	1.490	0.200	1.570	0.240	1.834
0.140	1.510	0.220	1.588		
0.160	1.517	0.240	1.618		
0.180	1.517	0.260	1.623		
0.200	1.524	0.280	1.642		
0.220	1.555				
0.240	1.550				
0.260	1.555				
0.280	1.570				

## d. Minimum Depth

Centerline		1.0 ft. Left		1.5 ft. Left		2.21 ft. Left	
Depth	Velocity	Depth	Velocity	Depth	Velocity	Depth	Velocity
ft.	fps	ft.	fps	ft.	fps	ft.	fps
0.010	0.695	0.010	0.915	0.010	0.447	0.010	0.200
0.015	0.708	0.020	1.036	0.020	0.425	0.020	0.200
0.020	0.722	0.030	1.162	0.030	0.425	0.030	0.200
0.025	0.749	0.040	1.265	0.040	0.400	0.040	0.200
0.030	0.775	0.050	1.280	0.050	0.400	0.060	0.200





## 7-2-4 (CONT'D.)

0.035	0.850	0.060	1.360	0.060	0.347	0.080	0.200
0.040	0.936	0.070	1.542	0.070	0.347	0.100	0.200
0.045	0.980	0.080	1.618	0.080	0.347	0.120	0.200
0.050	0.980	0.090	1.735	0.090	0.347	0.160	0.200
0.060	1.170	0.100	1.770	0.100	0.347	0.200	0.200
0.070	1.265	0.120	1.835	0.120	0.347	0.240	0.200
0.080	1.420	0.140	1.813	0.140	0.347		
0.090	1.505	0.160	1.758	0.160	0.347		
0.100	1.570	0.180	1.758	0.200	0.347		
0.120	1.700	0.200	1.770	0.240	0.347		
0.140	1.780	0.220	1.687				
0.160	1.824	0.240	1.735				
0.200	1.940						
0.240	2.030						

## B) Velocity Profile for Normal Depth Run No. 2

$$Q = 2 \text{ cfs}; S = 0.000131; y_n = 24.30 \text{ cm.}$$

Centerline		1 ft. Left		2 ft. Left	
Depth ft.	Velocity fps	Depth ft.	Velocity fps	Depth ft.	Velocity fps
0.010	0.200	0.010	0.347	0.010	0.401
0.020	0.200	0.050	0.401	0.100	0.547
0.030	0.245	0.100	0.401	0.200	0.650
0.040	0.315	0.150	0.491	0.300	0.665
0.050	0.347	0.200	0.547	0.400	0.665
0.060	0.315	0.250	0.566	0.500	0.665
0.070	0.315	0.300	0.602	0.600	0.665
0.080	0.375	0.350	0.650	0.700	0.665
0.090	0.375	0.400	0.665		
0.100	0.401	0.500	0.665		
0.120	0.425	0.600	0.694		
0.140	0.447	0.700	0.722		
0.160	0.401				
0.180	0.491				
0.200	0.491				
0.240	0.510				
0.280	0.510				
0.320	0.566				
0.360	0.547				
0.400	0.566				
0.500	0.633				
0.600	0.633				
0.700	0.650				



7-2-4 (CONT'D.)

## C) Velocity Profile for Normal Depth Run No. 10

 $Q = 1 \text{ cfs}; S = 0.00408; y_n = 5.35 \text{ cm.}$ 

Centerline		1 ft. Left		2 ft. Left		2.23 ft. Left	
Depth	Velocity	Depth	Velocity	Depth	Velocity	Depth	Velocity
ft.	fps	ft.	fps	ft.	fps	ft.	fps
0.010	0.665	0.010	0.750	0.010	0.775	0.010	0.775
0.015	0.695	0.020	0.775	0.020	0.775	0.020	0.775
0.020	0.750	0.030	0.825	0.030	0.775	0.030	0.775
0.025	0.775	0.040	0.875	0.040	0.875	0.040	0.825
0.030	0.825	0.050	1.015	0.050	0.915	0.060	0.980
0.035	0.875	0.060	1.075	0.060	1.035	0.080	1.145
0.040	0.915	0.070	1.145	0.070	1.095	0.100	1.230
0.050	1.180	0.080	1.250	0.080	1.180	0.120	1.340
0.060	1.215	0.090	1.330	0.100	1.340	0.140	1.475
0.070	1.265	0.100	1.390	0.120	1.505		
0.080	1.340	0.120	1.505	0.140	1.550		
0.090	1.410	0.140	1.580				
0.100	1.475						
0.120	1.540						
0.140	1.630						



TABLE 7-3 GEOMETRY II RAW and CALCULATED DATA.

1	2	3	4	5	6	7	8	9	10	11	12	13
Run NO	M	$P_n$	Q cfs	$y_n$ cm	$S_n$	M'	$I_q b$ $A n^2$	$y_1$ cm	$\frac{h_1^*}{y_n}$	$\left(\frac{P_n^2}{M'}\right)$	K	D
1	C.5	C.050	1.0	24.69	C.C0003	C.464	0.	24.32	0.00955	0.01161	1.85832	0.50180
2	C.5	C.050	1.0	24.69	C.C0003	C.464	4.1	24.29	0.00830	0.01161	1.69962	0.36721
3	C.5	C.050	1.0	24.69	C.C0003	C.464	8.2	24.34	0.01038	0.01161	1.99746	0.56668
4	C.5	C.050	1.0	24.69	C.C0003	C.464	13.7	24.24	0.00790	0.01161	1.57599	0.56668
5	C.5	C.050	1.0	24.69	C.C0003	C.464	13.7	24.28	0.00956	0.01161	1.85299	0.56668
6	C.7	C.065	1.0	24.65	C.C0003	C.675	0.	24.11	0.00249	0.00927	1.42707	0.50452
7	C.7	C.065	1.0	24.65	C.C0003	C.675	3.9	24.13	0.00333	0.00927	1.72052	0.5816
8	C.7	C.065	1.0	24.65	C.C0003	C.675	7.9	24.25	0.00832	0.00927	3.48124	0.56350
9	C.7	C.065	1.0	24.65	C.C0003	C.675	10.5	24.25	0.00748	0.00927	3.18778	0.56350
10	C.7	C.065	1.0	24.65	C.C0003	C.675	13.1	24.24	0.00790	0.00927	3.33451	0.56350
11	C.9	C.065	1.0	24.65	C.C0003	C.882	0.	24.23	0.00748	0.00543	5.44274	0.55660
12	C.9	C.065	1.0	24.65	C.C0003	C.882	3.9	24.25	0.00832	0.00543	5.94379	0.33751
13	C.9	C.065	1.0	24.65	C.C0003	C.882	7.8	24.26	0.00748	0.00543	6.19431	0.55661
14	C.9	C.065	1.0	24.65	C.C0003	C.882	10.3	24.27	0.00915	0.00543	6.44484	0.55661
15	C.9	C.065	1.0	24.65	C.C0003	C.882	12.9	24.28	0.00936	0.00543	6.69536	0.55661
16	C.9	C.065	2.0	9.60	C.C0230	C.886	0.	9.48	0.00816	0.19533	1.03596	0.48894
17	C.9	C.065	2.0	9.60	C.C0230	C.886	9.4	9.98	0.01837	0.19533	1.12771	0.60611
18	C.9	C.065	2.0	9.60	C.C0230	C.886	18.7	9.98	0.01837	0.19533	1.12771	0.60611
19	C.9	C.065	2.0	9.60	C.C0230	C.886	25.0	9.98	0.01837	0.19533	1.12771	0.60611
20	C.9	C.065	2.0	9.60	C.C0230	C.886	31.2	9.98	0.01837	0.19533	1.12771	0.60611
21	C.7	C.356	2.0	9.40	C.C0233	C.695	31.3	11.26	0.15918	0.32465	1.44173	0.
22	C.7	C.356	2.0	9.40	C.C0233	C.695	25.1	11.26	0.15918	0.32465	1.43601	0.81028
23	C.7	C.356	2.0	9.40	C.C0233	C.695	18.8	11.26	0.14898	0.32465	1.38466	0.81028
24	C.7	C.356	2.0	9.40	C.C0233	C.695	9.4	11.26	0.12755	0.32465	1.26550	0.61588
25	C.7	C.356	2.0	9.40	C.C0233	C.695	0.	16.77	0.09898	0.32465	1.0816	0.46325
26	C.5	C.356	2.0	9.40	C.C0233	C.495	0.	13.30	0.35714	0.64000	1.30955	0.45577
27	C.5	C.356	2.0	9.40	C.C0233	C.495	31.4	14.55	0.46469	0.64000	1.69398	0.
28	C.5	C.356	2.0	9.40	C.C0233	C.495	25.1	14.55	0.46469	0.64000	1.69398	1.19302
29	C.5	C.356	2.0	9.40	C.C0233	C.495	18.8	14.54	0.46327	0.64000	1.62892	1.19302
30	C.3	C.353	2.0	9.40	C.C0233	C.291	0.	19.53	0.95286	1.82389	1.13038	0.44446
31	C.3	C.353	2.0	9.40	C.C0233	C.291	9.6	23.12	1.35918	1.82389	1.53068	0.64304
32	C.3	C.353	2.0	9.40	C.C0233	C.291	19.2	23.09	1.35612	1.82389	1.52732	2.16718
33	C.3	C.353	2.0	9.40	C.C0233	C.291	25.6	22.65	1.31122	1.82389	1.52732	0.
34	C.3	C.353	2.0	9.40	C.C0233	C.291	32.1	22.65	1.31122	1.82389	1.47808	0.
35	C.5	C.353	2.0	9.40	C.C0233	C.463	0.	25.80	1.63265	0.72048	4.63614	0.45447
36	C.5	C.353	2.0	9.40	C.C0233	C.463	10.1	25.75	1.62755	0.72048	4.63614	0.45447
37	C.5	C.353	2.0	9.40	C.C0233	C.463	20.2	25.88	1.62755	0.72048	4.62191	0.62828
38	C.5	C.353	2.0	9.40	C.C0233	C.463	20.9	25.91	1.64082	0.72048	4.65891	1.27635
39	C.5	C.353	2.0	9.40	C.C0233	C.463	33.6	25.96	1.64898	0.72048	4.66745	0.
40	C.5	C.353	2.0	9.40	C.C0233	C.463	20.9	25.91	1.64898	0.72048	4.68168	0.
41	C.3	C.155	1.0	9.88	C.C0071	C.291	0.	13.53	0.34919	0.44904	1.64844	0.45966
42	C.3	C.155	1.0	9.88	C.C0071	C.291	9.5	14.47	0.46457	0.44904	2.16624	0.62090
43	C.3	C.155	1.0	9.88	C.C0071	C.291	19.1	14.15	0.43219	0.44904	2.02069	0.97483
44	C.3	C.155	1.0	9.88	C.C0071	C.291	25.4	14.62	0.47976	0.44904	2.23452	0.97483
45	C.3	C.155	1.0	9.88	C.C0071	C.291	31.8	14.38	0.45547	0.44904	2.12529	0.
46	C.5	C.155	1.0	9.88	C.C0071	C.495	0.	10.97	0.11032	0.15519	1.69444	0.47153
47	C.5	C.155	1.0	9.88	C.C0071	C.495	18.7	11.13	0.12652	0.15519	1.69444	0.47153
48	C.5	C.155	1.0	9.88	C.C0071	C.495	24.9	11.24	0.13765	0.15519	1.90135	0.53200
49	C.5	C.155	1.0	9.88	C.C0071	C.495	31.2	11.28	0.14170	0.15519	2.04376	0.
50	C.3	C.250	2.0	13.40	C.C0085	0.282	0.	20.64	0.54030	0.78593	1.48359	0.45353
51	C.3	C.250	2.0	13.40	C.C0085	0.282	7.3	23.60	0.76119	0.78593	2.04625	0.58627
52	C.3	C.250	2.0	13.40	C.C0085	0.282	14.5	23.33	0.74104	0.78593	2.01113	0.62965





Contd.

Run No	1	2	3	4	5	6	7	8	9	$10^* \frac{h_1}{y_n}$	$11^2 \left(\frac{h_1}{y_n}\right)$	12	13
		$P_n$	$Q$	$cfs$	$cms$	$S_n$	$M'$	$\frac{L_{db}}{A_{12}}$	$y_1$	$y_n$		$K$	$D$
53	C-2	0.250	2.0	13.40	C-00085	0.282	19.4	15.73	0.17388	0.78593	0.53376	1.34120	
54	C-5	0.250	2.0	13.40	C-00085	0.489	7.0	15.90	0.18734	0.56137	0.52617	0.51884	
55	C-5	0.250	2.0	13.40	C-00085	0.489	18.6	15.98	0.19254	0.26137	1.76837	0.71609	
56	C-5	0.250	2.0	13.40	C-00085	0.489	23.3	16.02	0.19552	0.26137	1.77134	0.71609	
57	C-5	0.250	2.0	13.40	C-00085	0.694	22.9	14.11	0.05299	0.15977	1.37853	0.48043	
58	C-7	0.250	2.0	13.40	C-00085	0.694	18.4	14.11	0.05299	0.15977	1.37853	0.48043	
59	C-7	0.250	2.0	13.40	C-00085	0.694	13.8	13.98	0.04328	0.12977	1.36720	0.60102	
60	C-7	0.250	2.0	13.40	C-00085	0.694	6.9	13.98	0.04328	0.12977	1.36720	0.60102	
61	C-7	0.250	2.0	13.40	C-00085	0.694	0.9	13.98	0.04328	0.12977	1.36720	0.60102	
62	C-7	0.250	2.0	13.40	C-00085	0.694	0.9	13.98	0.04328	0.12977	1.36720	0.60102	
63	C-5	0.141	3.0	25.38	C-00092	0.461	3.9	26.72	0.05280	0.09355	1.67639	0.59702	
64	C-5	0.141	3.0	25.38	C-00092	0.461	3.9	26.72	0.05280	0.09355	1.67639	0.59702	
65	C-5	0.141	3.0	25.38	C-00092	0.461	7.8	27.09	0.07289	0.09355	1.79302	0.59702	
66	C-5	0.141	3.0	25.38	C-00092	0.461	10.4	27.23	0.07289	0.09355	1.79302	0.59702	
67	C-5	0.141	3.0	25.38	C-00092	0.461	13.0	27.35	0.07762	0.09355	1.89301	0.59702	
68	C-7	0.141	3.0	25.38	C-00092	0.674	12.5	25.89	0.02206	0.04376	1.53866	0.58579	
69	C-7	0.141	3.0	25.38	C-00092	0.674	10.0	25.89	0.02049	0.04376	1.46764	0.58579	
70	C-7	0.141	3.0	25.38	C-00092	0.674	7.5	25.90	0.02049	0.04376	1.46764	0.58579	
71	C-7	0.141	3.0	25.38	C-00092	0.674	5.7	25.88	0.01970	0.04376	1.43214	0.42548	
72	C-7	0.141	3.0	25.38	C-00092	0.674	3.7	25.88	0.01970	0.04376	1.43214	0.42548	
73	C-5	0.300	3.0	15.45	C-00123	0.487	0.0	19.10	0.23625	0.37948	1.55479	0.50476	
74	C-5	0.300	3.0	15.45	C-00123	0.487	6.1	19.36	0.25307	0.37948	1.70139	0.50476	
75	C-5	0.300	3.0	15.45	C-00123	0.487	12.2	19.80	0.28155	0.37948	1.73144	0.88565	
76	C-5	0.300	3.0	15.45	C-00123	0.487	16.2	19.89	0.28738	0.37948	1.76466	0.88565	
77	C-5	0.300	3.0	15.45	C-00123	0.487	20.3	19.99	0.29385	0.37948	1.79481	0.88565	
78	C-7	0.300	3.0	15.45	C-00123	0.690	16.0	16.71	0.08479	0.18904	1.40929	0.59533	
79	C-7	0.300	3.0	15.45	C-00123	0.690	16.0	16.71	0.08479	0.18904	1.40929	0.59533	
80	C-7	0.300	3.0	15.45	C-00123	0.690	16.0	16.71	0.08479	0.18904	1.40929	0.59533	
81	C-7	0.300	3.0	15.45	C-00123	0.690	16.0	16.71	0.08479	0.18904	1.40929	0.59533	
82	C-7	0.300	3.0	15.45	C-00123	0.690	16.0	16.71	0.08479	0.18904	1.40929	0.59533	
83	C-7	0.300	3.0	15.45	C-00123	0.690	16.0	16.71	0.08479	0.18904	1.40929	0.59533	
84	C-7	0.300	3.0	15.45	C-00123	0.690	16.0	16.71	0.08479	0.18904	1.40929	0.59533	
85	C-5	0.450	3.0	11.61	C-00294	0.493	0.0	17.40	0.49871	0.83317	1.50768	0.63057	
86	C-5	0.450	3.0	11.61	C-00294	0.493	8.0	18.46	0.59001	0.83317	1.49492	1.38657	
87	C-5	0.450	3.0	11.61	C-00294	0.493	16.0	18.39	0.58398	0.83317	1.57860	1.38657	
88	C-5	0.450	3.0	11.61	C-00294	0.493	21.3	18.83	0.62188	0.83317	1.57286	0.1	
89	C-5	0.450	3.0	11.61	C-00294	0.493	26.6	18.80	0.61929	0.83317	1.57286	0.1	
90	C-7	0.450	3.0	11.61	C-00294	0.693	26.5	14.66	0.21102	0.42166	1.37707	0.94049	
91	C-7	0.450	3.0	11.61	C-00294	0.693	15.9	13.99	0.25672	0.42166	1.35940	0.94049	
92	C-7	0.450	3.0	11.61	C-00294	0.693	15.9	13.99	0.25672	0.42166	1.35940	0.94049	
93	C-7	0.450	3.0	11.61	C-00294	0.693	15.9	13.99	0.25672	0.42166	1.35940	0.94049	
94	C-2	0.200	1.0	10.00	C-00013	0.292	9.4	14.46	0.44600	0.46913	2.17263	0.62158	
95	C-2	0.200	1.0	13.42	C-00014	0.282	4.8	21.03	0.56706	0.78593	1.56053	0.58627	
96	C-5	0.100	1.0	14.83	C-00014	0.278	13.3	17.00	0.14633	0.12939	2.13037	0.60188	
97	C-5	0.100	1.0	14.83	C-00014	0.278	12.7	15.37	0.03641	0.04216	1.83755	0.58524	
98	C-5	0.100	1.0	14.83	C-00014	0.278	8.3	23.42	0.04007	0.08507	1.84615	0.63474	
99	C-5	0.100	1.0	14.83	C-00014	0.278	9.7	18.87	0.29590	0.37180	1.68302	0.61797	
100	C-3	0.400	2.0	9.77	C-00033	0.592	9.7	15.52	1.05306	1.90250	0.84672	0.64672	
101	C-5	0.400	2.0	9.77	C-00033	0.592	9.7	15.52	1.05306	1.90250	0.84672	0.64672	
102	C-7	0.400	3.0	12.65	C-00230	0.490	7.4	16.48	0.46037	0.66239	1.52433	0.57543	
103	C-5	0.400	3.0	12.65	C-00230	0.694	24.3	14.64	0.15731	0.33320	1.38322	0.82096	
104	C-5	0.400	3.0	12.65	C-00230	0.694	7.3	12.89	0.01897	0.19974	1.11666	0.50358	
105	C-5	0.400	3.0	15.39	C-00021	0.486	21.2	22.04	0.30214	0.41091	1.65183	0.92675	
106	C-7	0.400	3.0	15.39	C-00021	0.486	20.4	22.04	0.30214	0.41091	1.65183	0.92675	
107	C-7	0.400	3.0	15.39	C-00021	0.486	20.4	22.04	0.30214	0.41091	1.65183	0.92675	
108	C-5	0.150	3.0	25.48	C-00026	0.679	12.4	25.95	0.00845	0.11311	1.90989	0.44425	
109	C-5	0.150	3.0	25.48	C-00026	0.679	12.4	25.95	0.00845	0.11311	1.90989	0.44425	
110	C-5	0.150	3.0	25.48	C-00026	0.679	12.4	25.95	0.00845	0.11311	1.90989	0.44425	
111	C-5	0.150	3.0	25.48	C-00026	0.679	12.4	25.95	0.00845	0.11311	1.90989	0.44425	
112	C-7	0.100	3.0	32.87	C-00012	0.428	10.8	34.28	0.04290	0.05459	1.63374	0.58903	
113	C-7	0.100	3.0	32.87	C-00012	0.428	10.8	34.28	0.04290	0.05459	1.63374	0.58903	
114	C-7	0.100	3.0	32.87	C-00012	0.428	10.8	34.28	0.04290	0.05459	1.63374	0.58903	
115	C-7	0.100	3.0	32.87	C-00012	0.428	10.8	34.28	0.04290	0.05459	1.63374	0.58903	
116	C-7	0.100	3.0	32.87	C-00012	0.428	10.8	34.28	0.04290	0.05459	1.63374	0.58903	
117	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
118	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
119	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
120	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
121	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
122	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
123	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
124	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
125	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
126	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
127	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
128	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
129	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
130	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
131	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
132	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
133	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
134	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
135	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
136	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
137	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
138	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
139	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
140	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	
141	C-5	0.250	3.0	17.63	C-00085	0.684	15.9	21.95	0.04125	0.08550	1.49325	0.37874	



TABLE 7-4 GEOMETRY III RAW AND CALCULATED DATA.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Run No	M	F <sub>n</sub>	Q	y <sub>n</sub> cm	S <sub>n</sub>	M'	$\Phi_1$	y <sub>1</sub> cm	$\frac{h_1^*}{y_n}$	$(\frac{F_n}{M'})^2$	K	D	$(\frac{h_1^*}{y_n}) (\frac{M'}{F_n})^2$
W-1-1	0.5	0.096	3.0	32.70	0.00012	0.427	30.00	33.56	0.02630	0.05049	1.03070	0.23441	0.521
	0.5	0.096	3.0	32.70	0.00012	0.427	45.00	33.63	0.02844	0.05049	1.11463	0.27311	0.563
	0.5	0.096	3.0	32.70	0.00012	0.427	60.00	33.71	0.03089	0.05049	1.21055	0.35855	0.612
	0.5	0.096	3.0	32.70	0.00012	0.427	90.00	33.76	0.03242	0.05049	1.27051	0.37485	0.642
W-1-2	0.7	0.096	3.0	32.70	0.00012	0.652	30.00	33.90	0.03670	0.02166	3.25284	0.22092	1.694
	0.7	0.096	3.0	32.70	0.00012	0.652	45.00	32.94	0.00734	0.02166	0.67026	0.26626	0.339
	0.7	0.096	3.0	32.70	0.00012	0.652	60.00	32.95	0.00765	0.02166	0.6819	0.35389	0.353
	0.7	0.096	3.0	32.70	0.00012	0.652	90.00	32.95	0.00765	0.02166	0.6819	0.35389	0.353
W-1-3	0.7	0.147	3.0	24.65	0.00028	0.674	30.00	24.88	0.00933	0.04741	0.38360	0.23338	0.197
	0.7	0.147	3.0	24.65	0.00028	0.674	45.00	24.98	0.01339	0.04741	0.55047	0.27259	0.282
	0.7	0.147	3.0	24.65	0.00028	0.674	60.00	24.98	0.01339	0.04741	0.55047	0.27259	0.282
	0.7	0.147	3.0	24.65	0.00028	0.674	90.00	24.98	0.01339	0.04741	0.55047	0.27259	0.282
W-1-4	0.5	0.147	3.0	24.65	0.00028	0.462	30.00	25.87	0.04949	0.10092	0.95725	0.24605	0.480
	0.5	0.147	3.0	24.65	0.00028	0.462	45.00	26.12	0.05963	0.10092	1.15381	0.27884	0.591
	0.5	0.147	3.0	24.65	0.00028	0.462	60.00	26.21	0.06572	0.10092	1.22460	0.38129	0.627
	0.5	0.147	3.0	24.65	0.00028	0.462	90.00	26.27	0.06572	0.10092	1.27180	0.39293	0.651
W-1-5	0.5	0.201	3.0	20.00	0.00048	0.476	30.00	22.23	0.11150	0.17818	1.19983	0.25604	0.626
	0.5	0.201	3.0	20.00	0.00048	0.476	45.00	21.00	0.05000	0.17818	0.95000	0.28364	0.281
	0.5	0.201	3.0	20.00	0.00048	0.476	60.00	20.12	0.06060	0.17818	0.64132	0.40130	0.034
	0.5	0.201	3.0	20.00	0.00048	0.476	90.00	20.24	0.01200	0.17818	0.12830	0.40841	0.067
W-1-6	0.5	0.201	3.0	20.00	0.00048	0.683	30.00	20.35	0.01750	0.08639	0.38606	0.24339	0.203
	0.5	0.201	3.0	20.00	0.00048	0.683	45.00	20.42	0.02100	0.08639	0.46339	0.27754	0.243
	0.5	0.201	3.0	20.00	0.00048	0.683	60.00	20.48	0.02400	0.08639	0.52971	0.37599	0.278
	0.5	0.201	3.0	20.00	0.00048	0.683	90.00	20.48	0.02400	0.08639	0.52971	0.38879	0.278
W-1-7	0.9	0.201	3.0	20.00	0.00048	0.887	30.00	20.12	0.06060	0.05123	0.22302	0.23465	0.117
	0.9	0.201	3.0	20.00	0.00048	0.887	45.00	20.11	0.00501	0.05123	0.20443	0.37522	0.107
	0.9	0.201	3.0	20.00	0.00048	0.887	60.00	20.11	0.00501	0.05123	0.20443	0.37522	0.107
	0.9	0.201	3.0	20.00	0.00048	0.887	90.00	20.11	0.00501	0.05123	0.20443	0.37522	0.107
W-2-1	0.5	0.250	3.0	17.27	0.00084	0.482	30.00	19.49	0.12855	0.26938	0.69935	0.26356	0.374
	0.5	0.250	3.0	17.27	0.00084	0.482	45.00	19.49	0.12855	0.26938	0.89451	0.28717	0.477
	0.5	0.250	3.0	17.27	0.00084	0.482	60.00	19.92	0.15345	0.26938	1.07002	0.41651	0.570
	0.5	0.250	3.0	17.27	0.00084	0.482	90.00	20.28	0.17429	0.26938	1.21742	0.42005	0.647
W-2-2	0.5	0.250	3.0	17.27	0.00084	0.687	30.00	17.37	0.00579	0.13245	0.08092	0.25078	0.044
	0.5	0.250	3.0	17.27	0.00084	0.687	45.00	17.37	0.00579	0.13245	0.08092	0.25078	0.044
	0.5	0.250	3.0	17.27	0.00084	0.687	60.00	17.85	0.03358	0.13245	0.47087	0.28112	0.254
	0.5	0.250	3.0	17.27	0.00084	0.687	90.00	17.85	0.03358	0.13245	0.47087	0.28112	0.254
W-2-3	0.7	0.299	3.0	15.32	0.00123	0.690	30.00	15.81	0.03916	0.18824	0.30495	0.25703	0.170
	0.7	0.299	3.0	15.32	0.00123	0.690	45.00	15.92	0.03916	0.18824	0.30495	0.25703	0.170
	0.7	0.299	3.0	15.32	0.00123	0.690	60.00	16.09	0.05026	0.18824	0.48062	0.40329	0.208
	0.7	0.299	3.0	15.32	0.00123	0.690	90.00	16.16	0.05483	0.18824	0.52469	0.40994	0.291
W-2-5	0.5	0.299	3.0	15.32	0.00123	0.486	30.00	17.66	0.15274	0.37964	0.73454	0.402	0.402
	0.5	0.299	3.0	15.32	0.00123	0.486	45.00	17.93	0.17037	0.37964	0.82101	0.42957	0.449
	0.5	0.299	3.0	15.32	0.00123	0.486	60.00	18.48	0.20627	0.37964	0.98001	0.42957	0.543
	0.5	0.299	3.0	15.32	0.00123	0.486	90.00	18.85	0.23042	0.37964	1.11768	0.42997	0.607
W-2-7	0.9	0.299	3.0	15.32	0.00123	0.892	30.00	15.38	0.00392	0.11258	0.06214	0.24794	0.035
	0.9	0.299	3.0	15.32	0.00123	0.892	45.00	15.38	0.00392	0.11258	0.06214	0.24794	0.035
	0.9	0.299	3.0	15.32	0.00123	0.892	60.00	15.38	0.00392	0.11258	0.06214	0.24794	0.035
	0.9	0.299	3.0	15.32	0.00123	0.892	90.00	15.38	0.00392	0.11258	0.06214	0.24794	0.035





Run No.	1	2	3	4	5	6	7	8	9	$\frac{10}{y_n} \frac{h_1^*}{y_n}$	$11 \left( \frac{F_n^2}{M'} \right)$	12	13	14
	M	Fn	Q	cfs	$y_n$ cm	$S_n$	$M'$	$\phi_i$	$y_1$ cm			K	D	$\frac{14}{y_n} \left( \frac{M' 2}{F_n} \right)$
W-2-8	0.5	0.394	3.0		12.76	0.00220	0.490	30.00	16.82	0.31818	0.64533	0.86364	0.28018	0.493
	0.5	0.394	3.0		12.76	0.00220	0.490	45.00	17.07	0.33777	0.64533	0.91953	0.29480	0.523
	0.5	0.394	3.0		12.76	0.00220	0.490	60.00	17.12	0.34169	0.64533	0.93074	0.45058	0.529
	0.5	0.394	3.0		12.76	0.00220	0.490	90.00	17.43	0.36599	0.64533	1.00038	0.44576	0.567
	0.7	0.394	3.0		12.76	0.00220	0.693	30.00	13.74	0.07680	0.32291	0.39638	0.26692	0.238
	0.7	0.394	3.0		12.76	0.00220	0.693	45.00	13.82	0.08307	0.32291	0.42947	0.26692	0.257
	0.7	0.394	3.0		12.76	0.00220	0.693	60.00	13.89	0.08856	0.32291	0.45850	0.26236	0.274
	0.9	0.394	3.0		12.76	0.00220	0.693	90.00	14.01	0.09796	0.32291	0.50845	0.42526	0.303
	0.9	0.394	3.0		12.76	0.00220	0.895	30.00	12.81	0.00392	0.19382	0.03295	0.25755	0.020
	0.5	0.507	3.0		10.78	0.00360	0.493	30.00	12.84	0.00627	0.19382	0.05276	0.41075	0.032
W-3-1	0.5	0.507	3.0		10.78	0.00360	0.493	45.00	12.89	0.19573	1.05808	0.26365	0.29004	0.174
	0.5	0.507	3.0		10.78	0.00360	0.493	60.00	13.00	0.20594	1.05808	0.28227	0.29921	0.185
	0.5	0.507	3.0		10.78	0.00360	0.493	90.00	17.18	0.59369	1.05808	0.29811	0.47109	0.195
	0.5	0.507	3.0		10.78	0.00360	0.493	30.00	12.76	0.18367	0.53249	0.94530	0.46101	0.561
	0.7	0.507	3.0		10.78	0.00360	0.695	30.00	12.76	0.18367	0.53249	0.52389	0.27643	0.345
	0.7	0.507	3.0		10.78	0.00360	0.695	60.00	13.00	0.20594	0.53249	0.56088	0.29311	0.368
	0.7	0.507	3.0		10.78	0.00360	0.695	90.00	13.09	0.21429	0.53249	0.59237	0.42886	0.387
	0.9	0.507	3.0		10.78	0.00360	0.896	30.00	10.96	0.01670	0.32033	0.01826	0.43998	0.402
	0.9	0.507	3.0		10.78	0.00360	0.896	90.00	11.06	0.02597	0.32033	0.07285	0.26677	0.502
	0.3	0.406	2.0		9.54	0.00360	0.291	30.00	18.26	0.71405	1.94996	0.11398	0.42503	0.081
W-3-3	0.3	0.406	2.0		9.54	0.00360	0.291	45.00	18.81	0.97170	1.94996	0.86368	0.30273	0.469
	0.3	0.406	2.0		9.54	0.00360	0.291	60.00	18.97	0.98847	1.94996	0.93798	0.49773	0.498
	0.3	0.406	2.0		9.54	0.00360	0.291	90.00	19.24	1.01677	1.94996	0.96629	0.48058	0.507
	0.3	0.394	2.0		9.74	0.00220	0.290	30.00	18.55	0.90452	1.83732	0.49773	0.30167	0.521
	0.3	0.394	2.0		9.74	0.00220	0.290	45.00	18.90	0.94045	1.83732	0.91127	0.30167	0.492
	0.3	0.394	2.0		9.74	0.00220	0.290	60.00	19.14	0.96509	1.83732	0.94936	0.30420	0.512
	0.3	0.394	2.0		9.74	0.00220	0.290	90.00	19.30	0.98152	1.83732	0.97551	0.49508	0.525
	0.3	0.394	2.0		11.66	0.00135	0.289	30.00	17.85	0.98152	1.83732	0.99296	0.47863	0.534
	0.3	0.301	2.0		11.66	0.00135	0.289	45.00	17.85	0.53087	1.07956	0.92591	0.29045	0.492
	0.3	0.301	2.0		11.66	0.00135	0.289	60.00	18.29	0.56861	1.07956	0.99378	0.29934	0.527
W-3-5	0.3	0.301	2.0		11.66	0.00135	0.289	90.00	18.90	0.62093	1.07956	1.08811	0.47194	0.575
	0.3	0.301	2.0		8.73	0.00088	0.292	30.00	19.65	0.68525	1.07956	1.20441	0.46164	0.635
	0.3	0.232	1.0		8.73	0.00088	0.292	45.00	11.85	0.35739	0.62957	0.62957	0.27969	0.568
	0.3	0.232	1.0		8.73	0.00088	0.292	60.00	12.09	0.38488	0.62957	1.08843	0.29458	0.611
	0.3	0.232	1.0		8.73	0.00088	0.292	90.00	12.25	0.40321	0.62957	1.17358	0.44958	0.640
	0.3	0.131	1.0		12.80	0.00031	0.283	30.00	13.68	0.44101	0.62957	1.23041	0.44501	0.700
	0.3	0.131	1.0		12.80	0.00031	0.283	45.00	13.97	0.06875	0.21297	0.63365	0.25926	0.323
	0.3	0.131	1.0		12.80	0.00031	0.283	60.00	14.13	0.06875	0.21297	0.84295	0.28516	0.429
	0.3	0.103	1.0		14.96	0.00014	0.276	30.00	16.23	0.10391	0.21297	0.95852	0.40780	0.488
	0.3	0.103	1.0		14.96	0.00014	0.276	45.00	16.52	0.12500	0.21297	1.15368	0.41340	0.587
W-4-3	0.3	0.103	1.0		14.96	0.00014	0.276	60.00	16.63	0.08489	0.13993	1.19957	0.25175	0.607
	0.3	0.103	1.0		14.96	0.00014	0.276	90.00	16.73	0.10428	0.13993	1.47393	0.28159	0.745
	0.3	0.103	1.0		14.96	0.00014	0.276	30.00	16.63	0.11163	0.13993	1.57803	0.39267	0.798
	0.3	0.103	1.0		14.96	0.00014	0.276	45.00	16.73	0.11832	0.13993	1.67269	0.40176	0.846
	0.3	0.103	1.0		14.96	0.00014	0.276	60.00	16.73	0.11832	0.13993	1.67269	0.40176	0.846
	0.3	0.103	1.0		14.96	0.00014	0.276	90.00	16.73	0.11832	0.13993	1.67269	0.40176	0.846
	0.3	0.103	1.0		14.96	0.00014	0.276	30.00	16.73	0.11832	0.13993	1.67269	0.40176	0.846
	0.3	0.103	1.0		14.96	0.00014	0.276	45.00	16.73	0.11832	0.13993	1.67269	0.40176	0.846
	0.3	0.103	1.0		14.96	0.00014	0.276	60.00	16.73	0.11832	0.13993	1.67269	0.40176	0.846
	0.3	0.103	1.0		14.96	0.00014	0.276	90.00	16.73	0.11832	0.13993	1.67269	0.40176	0.846



TABLE 7-5 - GEOMETRY IV RAW and CALCULATED DATA.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Run No	M	F <sub>n</sub>	Q	y <sub>n</sub> cm	S <sub>n</sub>	M'	e	y <sub>1</sub> cm	$\frac{h_1}{y_n}$	$\left(\frac{F_n}{M'}\right)^2$	K	D	$\frac{h_1}{y_n} \left(\frac{M'}{F_n}\right)$
E-2-1	0.3	0.108	1.0	14.57	0.00014	0.278	0.	16.70	0.14619	0.15004	1.92652	0.55879	0.974
	0.3	0.108	1.0	14.57	0.00014	0.278	0.80	16.66	0.14345	0.15004	1.89027	0.54000	0.956
	0.3	0.108	1.0	14.57	0.00014	0.278	0.85	16.68	0.14482	0.15004	1.90840	0.54346	0.965
E-2-3	0.3	0.108	1.0	14.57	0.00014	0.278	0.90	16.69	0.14550	0.15004	1.91746	0.57252	0.970
	0.3	0.108	1.0	14.57	0.00014	0.278	1.00	16.85	0.14550	0.15004	1.91746	0.58354	0.970
	0.3	0.151	1.0	11.63	0.00038	0.286	0.	14.51	0.24850	0.27786	1.75339	0.56834	1.043
E-3-1	0.3	0.151	1.0	11.63	0.00038	0.286	0.80	14.51	0.24764	0.27786	1.74729	0.55687	0.894
	0.3	0.151	1.0	11.63	0.00038	0.286	0.85	14.59	0.25451	0.27786	1.79611	0.56107	0.891
	0.3	0.151	1.0	11.63	0.00038	0.286	0.90	14.48	0.24506	0.27786	1.72898	0.56107	0.916
E-3-3	0.3	0.151	1.0	11.63	0.00038	0.286	0.95	14.53	0.24536	0.27786	1.72898	0.56376	0.882
	0.3	0.196	1.0	9.78	0.00060	0.290	1.00	14.70	0.26397	0.27786	1.75949	0.57760	0.897
	0.3	0.196	1.0	9.78	0.00060	0.290	0.	13.51	0.38139	0.45397	1.86326	0.61759	0.950
E-3-5	0.3	0.243	1.0	8.46	0.00110	0.293	0.80	12.89	0.52364	0.68956	1.6019	0.55404	0.759
	0.3	0.243	1.0	8.46	0.00110	0.293	0.85	12.91	0.52364	0.68956	1.6019	0.55404	0.759
	0.3	0.243	1.0	8.46	0.00110	0.293	0.90	12.94	0.52600	0.68956	1.46691	0.61719	0.763
E-4-1	0.3	0.316	2.0	11.27	0.00120	0.287	0.	19.88	0.36619	0.68956	1.47699	0.55756	0.763
	0.3	0.316	2.0	11.27	0.00120	0.287	0.80	20.34	0.40479	0.68956	1.46691	0.55756	0.763
	0.3	0.316	2.0	11.27	0.00120	0.287	0.85	20.27	0.40479	0.68956	1.46691	0.55756	0.763
E-4-3	0.3	0.407	2.0	9.52	0.00210	0.291	0.80	19.99	0.79858	1.21396	1.58123	0.60207	0.821
	0.3	0.407	2.0	9.52	0.00210	0.291	0.85	20.02	0.79858	1.21396	1.58123	0.60207	0.821
	0.3	0.407	2.0	9.52	0.00210	0.291	0.90	20.06	1.0714	1.96174	1.04585	0.55356	0.562
E-5-1	0.7	0.094	3.0	33.09	0.00012	0.651	1.00	33.38	0.00816	0.02098	0.76953	0.63290	0.389
	0.7	0.094	3.0	33.09	0.00012	0.651	0.80	33.37	0.00846	0.02098	0.76953	0.63290	0.389
	0.7	0.094	3.0	33.09	0.00012	0.651	0.85	33.43	0.01027	0.02098	0.76953	0.63290	0.389
E-5-3	0.7	0.094	3.0	33.09	0.00012	0.651	0.90	33.43	0.01027	0.02098	0.76953	0.63290	0.389
	0.7	0.094	3.0	33.09	0.00012	0.651	0.95	33.46	0.00937	0.02098	0.76953	0.63290	0.389
	0.7	0.094	3.0	33.09	0.00012	0.651	1.00	33.46	0.01118	0.02098	0.76953	0.63290	0.389





## 7-5 Contd.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Run No.	M	F <sub>n</sub>	Q cfs	y <sub>n</sub> cm	S <sub>n</sub>	M'	e	y <sub>l</sub> cm	$\frac{h_1^*}{y_n}$	$\left(\frac{F_n^2}{M'}\right)$	K	D	$\frac{h_1^*}{y_n} \left(\frac{M'}{F_n}\right)$
E-5-3	0.5	0.044	3.0	33.09	0.0012	0.425	0.	34.30	0.03657	0.04922	1.47087	0.56293	0.743
	0.5	0.094	3.0	33.09	0.0012	0.425	0.80	34.27	0.03566	0.04922	1.43439	0.62903	0.725
	0.5	0.094	3.0	33.09	0.0012	0.425	0.85	34.20	0.03596	0.04922	1.44655	0.56781	0.731
	0.5	0.094	3.0	33.09	0.0012	0.425	0.90	34.29	0.03626	0.04922	1.45671	0.58869	0.737
	0.5	0.094	3.0	33.09	0.0012	0.425	0.95	34.33	0.03747	0.04922	1.50736	0.59444	0.761
E-6-1	0.5	0.094	3.0	33.09	0.0012	0.425	1.00	34.37	0.03929	0.04922	1.59034	0.64826	0.798
	0.5	0.142	3.0	25.19	0.0027	0.460	0.	26.85	0.06590	0.09533	1.35211	0.56021	0.691
	0.5	0.142	3.0	25.19	0.0027	0.460	0.80	26.90	0.06788	0.09533	1.32111	0.62604	0.712
	0.5	0.142	3.0	25.19	0.0027	0.460	0.85	26.94	0.06947	0.09533	1.32993	0.62604	0.712
	0.5	0.142	3.0	25.19	0.0027	0.460	0.90	26.94	0.06947	0.09533	1.32993	0.62604	0.712
E-6-3	0.5	0.142	3.0	25.19	0.0027	0.460	0.95	27.01	0.07225	0.09533	1.42558	0.56523	0.729
	0.5	0.142	3.0	25.19	0.0027	0.460	1.00	27.06	0.07424	0.09533	1.42558	0.57904	0.729
	0.5	0.142	3.0	25.19	0.0027	0.460	0.	25.71	0.02064	0.09533	1.48273	0.58795	0.758
	0.5	0.142	3.0	25.19	0.0027	0.460	0.80	25.71	0.02064	0.09533	1.52356	0.63637	0.779
	0.5	0.142	3.0	25.19	0.0027	0.460	0.85	25.71	0.02064	0.09533	1.52356	0.63637	0.779
E-6-5	0.5	0.142	3.0	25.19	0.0027	0.460	0.90	25.71	0.02064	0.09533	1.52356	0.63637	0.779
	0.5	0.142	3.0	25.19	0.0027	0.460	0.95	25.71	0.02064	0.09533	1.52356	0.63637	0.779
	0.5	0.142	3.0	25.19	0.0027	0.460	1.00	25.71	0.02064	0.09533	1.52356	0.63637	0.779
	0.5	0.142	3.0	25.19	0.0027	0.460	0.	20.84	0.03630	0.08503	0.81536	0.56057	0.380
	0.5	0.142	3.0	25.19	0.0027	0.460	0.80	20.84	0.03630	0.08503	0.81536	0.56057	0.380
E-6-7	0.5	0.142	3.0	25.19	0.0027	0.460	0.85	20.84	0.03630	0.08503	0.81536	0.56057	0.380
	0.5	0.142	3.0	25.19	0.0027	0.460	0.90	20.84	0.03630	0.08503	0.81536	0.56057	0.380
	0.5	0.142	3.0	25.19	0.0027	0.460	0.95	20.84	0.03630	0.08503	0.81536	0.56057	0.380
	0.5	0.142	3.0	25.19	0.0027	0.460	1.00	20.84	0.03630	0.08503	0.81536	0.56057	0.380
	0.5	0.142	3.0	25.19	0.0027	0.460	0.	20.84	0.03630	0.08503	0.81536	0.56057	0.380
E-7-1	0.5	0.249	3.0	17.31	0.0046	0.475	0.	22.62	0.04276	0.08503	0.87376	0.58907	0.456
	0.5	0.249	3.0	17.31	0.0046	0.475	0.80	22.62	0.04276	0.08503	0.87376	0.58907	0.456
	0.5	0.249	3.0	17.31	0.0046	0.475	0.85	22.62	0.04276	0.08503	0.87376	0.58907	0.456
	0.5	0.249	3.0	17.31	0.0046	0.475	0.90	22.62	0.04276	0.08503	0.87376	0.58907	0.456
	0.5	0.249	3.0	17.31	0.0046	0.475	0.95	22.62	0.04276	0.08503	0.87376	0.58907	0.456
E-7-3	0.5	0.249	3.0	17.31	0.0046	0.475	1.00	22.62	0.04276	0.08503	0.87376	0.58907	0.456
	0.5	0.249	3.0	17.31	0.0046	0.475	0.	20.58	0.03978	0.08503	0.89376	0.58907	0.456
	0.5	0.249	3.0	17.31	0.0046	0.475	0.80	20.58	0.03978	0.08503	0.89376	0.58907	0.456
	0.5	0.249	3.0	17.31	0.0046	0.475	0.85	20.58	0.03978	0.08503	0.89376	0.58907	0.456
	0.5	0.249	3.0	17.31	0.0046	0.475	0.90	20.58	0.03978	0.08503	0.89376	0.58907	0.456
E-7-6	0.5	0.304	3.0	15.15	0.0011	0.486	0.	19.21	0.06799	0.39205	1.25984	0.55794	0.684
	0.5	0.304	3.0	15.15	0.0011	0.486	0.80	19.21	0.06799	0.39205	1.25984	0.55794	0.684
	0.5	0.304	3.0	15.15	0.0011	0.486	0.85	19.21	0.06799	0.39205	1.25984	0.55794	0.684
	0.5	0.304	3.0	15.15	0.0011	0.486	0.90	19.21	0.06799	0.39205	1.25984	0.55794	0.684
	0.5	0.304	3.0	15.15	0.0011	0.486	0.95	19.21	0.06799	0.39205	1.25984	0.55794	0.684





7-5 Contd.

Run No	1	2	3	4	5	6	7	8	9	10	11	12	13	14
		M	F <sub>n</sub>	Q	y <sub>n</sub> cm	S <sub>n</sub>	M'	e	y <sub>1</sub> cm	$\frac{h_1^*}{y_n}$	$(\frac{F_n^2}{M'})$	K	D	$\frac{h_1^*}{y_n} (\frac{M'}{F_n})$
E-7-8		0.7	C-304	3.0	15.15	C-00011	C-690	0.	16.24	0.07195	0.19452	0.66554	0.55798	0.370
		0.7	C-304	3.0	15.15	C-00011	C-690	0.80	16.27	0.07393	0.19452	0.68407	0.62283	0.380
		0.7	C-304	3.0	15.15	C-00011	C-690	0.85	16.35	0.07921	0.19452	0.73352	0.56245	0.407
		0.7	C-304	3.0	15.15	C-00011	C-690	0.90	16.34	0.07855	0.19452	0.72733	0.56881	0.404
		0.7	C-304	3.0	15.15	C-00011	C-690	0.95	16.41	0.08317	0.19452	0.77065	0.58103	0.428
		0.7	C-304	3.0	15.15	C-00011	C-690	1.00	16.54	0.07175	0.19452	0.85125	0.62379	0.472
E-8-1		0.7	C-304	3.0	15.15	C-00011	C-690	0.	14.18	0.13440	0.34321	0.65457	0.5621	0.392
		0.7	C-406	3.0	12.50	C-00220	C-693	0.80	14.30	0.14400	0.34321	0.70302	0.62029	0.420
		0.7	C-406	3.0	12.50	C-00220	C-693	0.85	14.31	0.14480	0.34321	0.70707	0.56025	0.422
		0.7	C-406	3.0	12.50	C-00220	C-693	0.90	14.31	0.14480	0.34321	0.70707	0.56079	0.422
		0.7	C-406	3.0	12.50	C-00220	C-693	0.95	14.42	0.15360	0.34321	0.75166	0.57558	0.448
		0.7	C-406	3.0	12.50	C-00220	C-693	1.00	14.60	0.16800	0.34321	0.82495	0.61395	0.489
E-8-3		0.5	C-406	3.0	12.50	C-00220	C-491	0.	17.97	0.43760	0.68533	1.12790	0.53406	0.639
		0.5	C-406	3.0	12.50	C-00220	C-491	0.80	18.00	0.44000	0.68533	1.13444	0.61721	0.642
		0.5	C-406	3.0	12.50	C-00220	C-491	0.85	17.89	0.43120	0.68533	1.11048	0.55759	0.629
		0.5	C-406	3.0	12.50	C-00220	C-491	0.90	18.07	0.44560	0.68533	1.14970	0.55118	0.650
		0.5	C-406	3.0	12.50	C-00220	C-491	0.95	18.18	0.45440	0.68533	1.17372	0.56901	0.663
E-8-5		0.5	C-406	3.0	12.50	C-00220	C-491	1.00	18.56	0.48480	0.68533	1.25690	0.60217	0.707
		0.5	C-526	3.0	10.52	C-00360	C-493	0.	17.58	0.67110	1.13695	0.99297	0.55249	0.590
		0.5	C-526	3.0	10.52	C-00360	C-493	0.80	17.66	0.67871	1.13695	1.00540	0.61497	0.597
		0.5	C-526	3.0	10.52	C-00360	C-493	0.85	17.64	0.67681	1.13695	1.00229	0.55564	0.595
		0.5	C-526	3.0	10.52	C-00360	C-493	0.90	17.63	0.67586	1.13695	1.00073	0.54425	0.594
		0.5	C-526	3.0	10.52	C-00360	C-493	0.95	17.79	0.69106	1.13695	1.02563	0.56425	0.608
		0.5	C-583	3.0	5.82	C-00360	C-494	1.00	18.10	0.84318	1.39302	1.00367	0.59033	0.605
E-8-7		0.7	C-526	3.0	10.52	C-00360	C-695	0.	13.36	0.26996	0.57257	0.72253	0.55462	0.471
		0.7	C-526	3.0	10.52	C-00360	C-695	0.80	13.32	0.26616	0.57257	0.71141	0.61801	0.465
		0.7	C-526	3.0	10.52	C-00360	C-695	0.85	13.49	0.28232	0.57257	0.75880	0.53828	0.493
		0.7	C-526	3.0	10.52	C-00360	C-695	0.90	13.56	0.28897	0.57257	0.77840	0.55366	0.505
		0.7	C-526	3.0	10.52	C-00360	C-695	0.95	13.72	0.30418	0.57257	0.82343	0.57071	0.531
		0.7	C-526	3.0	10.52	C-00360	C-695	1.00	13.94	0.32510	0.57257	0.88580	0.60521	0.568



TABLE 7-6. GEOMETRY  $V_a$  RAW and CALCULATED DATA.

1	2	3	4	5	6	7	8	9	10	11	12	13
Run No.	N	$F_n$	$Q$ cfs	$y_n$ cms	$S_n$	$M'$	$\phi_2$	$y_1$ cms	$\frac{h_1^*}{y_n}$	$\frac{F_n^2}{M'}$	K	D
										$(\frac{h_1}{y_n})^2 (\frac{M'}{F_n})^2$		
S-1-1	0.5	0.502	3.0	10.85	0.00360	0.493	0.	17.95	0.65438	1.03811	1.26071	0.58523
	0.5	0.502	3.0	10.85	0.00360	0.493	15.0	17.38	0.60184	1.03811	1.15949	0.63151
	0.5	0.502	3.0	10.85	0.00360	0.493	30.0	16.54	0.52442	1.03811	1.01034	0.53265
	0.5	0.502	3.0	10.85	0.00360	0.493	45.0	15.32	0.41198	1.03811	0.79371	0.43046
	0.5	0.502	3.0	10.85	0.00360	0.493	0.	13.60	0.25346	1.03811	0.48830	0.58523
S-1-2	0.5	0.502	3.0	10.85	0.00360	0.493	15.0	13.28	0.22394	1.03811	0.43148	0.63151
	0.5	0.502	3.0	10.85	0.00360	0.493	30.0	13.13	0.21014	1.03811	0.40485	0.53265
	0.5	0.502	3.0	10.85	0.00360	0.493	45.0	12.68	0.16866	1.03811	0.32494	0.43046
	0.5	0.502	3.0	10.85	0.00360	0.493	0.	11.17	0.03139	1.03811	0.19873	0.55936
	0.5	0.502	3.0	10.85	0.00360	0.493	15.0	11.13	0.02770	1.03811	0.17535	0.55208
S-1-3	0.9	0.504	3.0	10.83	0.00210	0.896	0.	18.28	0.43036	0.64239	1.33987	0.57665
	0.9	0.504	3.0	10.83	0.00210	0.896	15.0	17.89	0.39984	0.64239	1.24486	0.59817
	0.9	0.504	3.0	10.83	0.00210	0.896	30.0	17.21	0.34664	0.64239	1.07921	0.51683
	0.9	0.504	3.0	10.83	0.00210	0.896	45.0	16.10	0.25978	0.64239	0.80879	0.41247
	0.9	0.504	3.0	10.83	0.00210	0.896	0.	14.45	0.13067	0.64239	0.81310	0.55972
S-1-4	0.7	0.393	3.0	12.78	0.00210	0.693	0.	14.36	0.12363	0.32142	0.76928	0.55315
	0.7	0.393	3.0	12.78	0.00210	0.693	15.0	14.36	0.12363	0.32142	0.76928	0.55315
	0.7	0.393	3.0	12.78	0.00210	0.693	30.0	14.19	0.11033	0.32142	0.68651	0.49484
	0.7	0.393	3.0	12.78	0.00210	0.693	45.0	13.81	0.08059	0.32142	0.50149	0.38785
	0.7	0.393	3.0	12.78	0.00210	0.693	0.	16.72	0.06497	0.32142	0.76182	0.54696
S-1-5	0.7	0.289	3.0	15.70	0.00120	0.690	0.	16.58	0.05605	0.17516	0.64001	0.51648
	0.7	0.289	3.0	15.70	0.00120	0.690	15.0	16.55	0.05605	0.17516	0.61819	0.47653
	0.7	0.289	3.0	15.70	0.00120	0.690	30.0	16.36	0.04204	0.17516	0.48000	0.36747
	0.7	0.289	3.0	15.70	0.00120	0.690	45.0	16.36	0.04204	0.17516	0.48000	0.36747
	0.7	0.289	3.0	15.70	0.00120	0.690	0.	19.69	0.25414	0.35380	1.43664	0.56177
S-1-6	0.5	0.289	3.0	15.70	0.00120	0.485	15.0	19.41	0.23631	0.35380	1.33582	0.55918
	0.5	0.289	3.0	15.70	0.00120	0.485	30.0	18.87	0.20191	0.35380	1.14139	0.49783
	0.5	0.289	3.0	15.70	0.00120	0.485	45.0	18.05	0.14968	0.35380	0.86614	0.39117
	0.5	0.289	3.0	15.70	0.00120	0.485	0.	22.98	0.11825	0.16525	1.43113	0.54575
	0.5	0.289	3.0	15.70	0.00120	0.485	15.0	22.79	0.10900	0.16525	1.31923	0.51309
S-2-1	0.5	0.193	3.0	20.55	0.00048	0.474	0.	22.98	0.08954	0.16525	0.08954	0.47459
	0.5	0.193	3.0	20.55	0.00048	0.474	15.0	22.98	0.08954	0.16525	0.08954	0.47459
	0.5	0.193	3.0	20.55	0.00048	0.474	30.0	22.98	0.08954	0.16525	0.08954	0.47459
	0.5	0.193	3.0	20.55	0.00048	0.474	45.0	22.98	0.08954	0.16525	0.08954	0.47459
	0.5	0.193	3.0	20.55	0.00048	0.474	0.	21.15	0.02920	0.07986	0.73117	0.53088
S-2-2	0.7	0.193	3.0	20.55	0.00048	0.682	15.0	21.10	0.02676	0.07986	0.67024	0.47262
	0.7	0.193	3.0	20.55	0.00048	0.682	30.0	21.00	0.02190	0.07986	0.56838	0.45341
	0.7	0.193	3.0	20.55	0.00048	0.682	45.0	20.91	0.01752	0.07986	0.43870	0.34269
	0.7	0.193	3.0	20.55	0.00048	0.682	0.	33.38	0.00815	0.02095	0.77852	0.50456
	0.7	0.193	3.0	20.55	0.00048	0.682	15.0	33.38	0.00815	0.02095	0.77852	0.50456
S-2-3	0.7	0.094	3.0	33.11	0.00012	0.651	15.0	33.38	0.00815	0.02095	0.77852	0.50456
	0.7	0.094	3.0	33.11	0.00012	0.651	30.0	33.38	0.00815	0.02095	0.77852	0.50456
	0.7	0.094	3.0	33.11	0.00012	0.651	45.0	33.38	0.00815	0.02095	0.77852	0.50456
	0.7	0.094	3.0	33.11	0.00012	0.651	0.	33.38	0.00815	0.02095	0.77852	0.50456
	0.7	0.094	3.0	33.11	0.00012	0.651	15.0	33.38	0.00815	0.02095	0.77852	0.50456
S-2-4	0.5	0.094	3.0	33.11	0.00012	0.425	15.0	33.38	0.00815	0.02095	0.77852	0.50456
	0.5	0.094	3.0	33.11	0.00012	0.425	30.0	33.38	0.00815	0.02095	0.77852	0.50456
	0.5	0.094	3.0	33.11	0.00012	0.425	45.0	33.38	0.00815	0.02095	0.77852	0.50456
	0.5	0.094	3.0	33.11	0.00012	0.425	0.	33.38	0.00815	0.02095	0.77852	0.50456
	0.5	0.094	3.0	33.11	0.00012	0.425	15.0	33.38	0.00815	0.02095	0.77852	0.50456
S-2-5	0.3	0.105	1.0	14.78	0.00014	0.277	15.0	17.07	0.15494	0.14447	2.14500	0.32822
	0.3	0.105	1.0	14.78	0.00014	0.277	30.0	17.07	0.15494	0.14447	2.14500	0.32822
	0.3	0.105	1.0	14.78	0.00014	0.277	45.0	16.52	0.12723	0.14447	2.10753	0.50536
	0.3	0.105	1.0	14.78	0.00014	0.277	0.	16.52	0.11773	0.14447	2.10753	0.50536
	0.3	0.105	1.0	14.78	0.00014	0.277	15.0	16.52	0.11773	0.14447	2.10753	0.50536
S-2-6	0.3	0.189	1.0	10.00	0.00013	0.290	0.	13.95	0.09675	0.42598	1.62982	0.47060
	0.3	0.189	1.0	10.00	0.00013	0.290	15.0	13.95	0.09675	0.42598	1.62982	0.47060
	0.3	0.189	1.0	10.00	0.00013	0.290	30.0	13.95	0.09675	0.42598	1.62982	0.47060
	0.3	0.189	1.0	10.00	0.00013	0.290	45.0	13.95	0.09675	0.42598	1.62982	0.47060
	0.3	0.189	1.0	10.00	0.00013	0.290	0.	13.95	0.09675	0.42598	1.62982	0.47060





7-6 Contd.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Run No.	M	F <sub>n</sub>	Q	y <sub>n</sub> cms	S <sub>n</sub>	M'		y <sub>1</sub> cms	$\frac{h_1^*}{y_n}$	$\left(\frac{F_n}{M'}\right)^2$	K	D	$\left(\frac{h_1}{y_n}\right) \left(\frac{M'}{R}\right)^2$
S-3-1	0.3	0.189	1.0	10.00	0.00013	0.290	30.00	13.04	0.30400	0.42598	1.42729	0.50367	0.714
	0.3	0.303	2.0	11.60	0.00013	0.286	0.	20.90	0.80172	1.11951	1.43228	0.58691	0.716
	0.3	0.303	2.0	11.60	0.00013	0.286	15.00	20.40	0.75862	1.11951	1.35528	0.63692	0.678
	0.3	0.303	2.0	11.60	0.00013	0.286	30.00	19.28	0.66207	1.11951	1.18279	0.53518	0.591
	0.3	0.303	2.0	11.60	0.00013	0.286	45.00	18.08	0.55862	1.11951	0.99798	0.43335	0.499
S-3-2	0.3	0.365	2.0	9.88	0.00220	0.290	0.	20.89	1.11437	1.76376	1.26363	0.59713	0.632
	0.3	0.385	2.0	9.88	0.00220	0.290	15.00	20.29	1.05364	1.76376	1.19477	0.67049	0.597
	0.3	0.385	2.0	9.88	0.00220	0.290	30.00	18.59	0.88158	1.76376	0.99966	0.55068	0.500
	0.3	0.385	2.0	9.88	0.00220	0.290	45.00	17.51	0.77227	1.76376	0.87570	0.45122	0.438
S-3-3	0.3	0.480	2.0	8.53	0.00370	0.293	0.	20.22	1.36962	2.69036	1.01817	0.60679	0.509
	0.3	0.480	2.0	8.53	0.00370	0.293	15.00	19.89	1.33095	2.69036	0.98942	0.70325	0.495
	0.3	0.480	2.0	8.53	0.00370	0.293	30.00	18.13	1.12469	2.69036	0.83609	0.56568	0.418
	0.3	0.480	2.0	8.53	0.00370	0.293	45.00	16.95	0.98641	2.69036	0.73329	0.46848	0.367
S-4-1	0.5	0.139	3.0	25.53	0.00380	0.459	0.	27.22	0.06620	0.09205	1.43828	0.53375	0.719
	0.5	0.139	3.0	25.53	0.00380	0.459	15.00	27.01	0.05797	0.09205	1.25956	0.48026	0.630
	0.5	0.139	3.0	25.53	0.00380	0.459	30.00	26.73	0.04700	0.09205	1.02127	0.45747	0.511
	0.5	0.139	3.0	25.53	0.00380	0.459	45.00	26.41	0.03447	0.09205	0.74893	0.34704	0.374
	0.7	0.139	3.0	25.53	0.00380	0.672	0.	25.88	0.01371	0.04293	0.63874	0.51850	0.319
	0.7	0.139	3.0	25.53	0.00380	0.672	15.00	25.88	0.01371	0.04293	0.63874	0.44050	0.319
	0.7	0.139	3.0	25.53	0.00380	0.672	30.00	25.81	0.01097	0.04293	0.51099	0.43607	0.255
	0.7	0.139	3.0	25.53	0.00380	0.672	45.00	25.74	0.00823	0.04293	0.38324	0.32429	0.192
S-4-2	0.3	0.142	1.0	12.12	0.00040	0.285	0.	15.18	0.25248	0.24765	2.00395	0.55421	1.019
	0.3	0.142	1.0	12.12	0.00040	0.285	15.00	15.00	0.23762	0.24765	1.91901	0.53709	0.960
	0.3	0.142	1.0	12.12	0.00040	0.285	30.00	14.36	0.18482	0.24765	1.49257	0.48680	0.746
	0.3	0.142	1.0	12.12	0.00040	0.285	45.00	14.07	0.16089	0.24765	1.28766	0.37896	0.650
S-5-1	0.3	0.231	1.0	8.76	0.00110	0.292	0.	13.48	0.53881	0.62335	1.72876	0.57399	0.864
	0.3	0.231	1.0	8.76	0.00110	0.292	15.00	13.33	0.52169	0.62335	1.67382	0.59614	0.837
	0.3	0.231	1.0	8.76	0.00110	0.292	30.00	12.46	0.42237	0.62335	1.35517	0.51586	0.678
	0.3	0.231	1.0	8.76	0.00110	0.292	45.00	11.98	0.36758	0.62335	1.17937	0.44137	0.590
S-5-2	0.5	0.220	3.0	18.80	0.00089	0.478	0.	20.97	0.11543	0.21186	1.08962	0.55093	0.545
	0.5	0.220	3.0	18.80	0.00089	0.478	15.00	20.76	0.10426	0.21186	0.98417	0.52770	0.492
	0.5	0.220	3.0	18.80	0.00089	0.478	30.00	20.30	0.07979	0.21186	0.75319	0.48260	0.377
	0.5	0.220	3.0	18.80	0.00089	0.478	45.00	19.65	0.04521	0.21186	0.42681	0.37374	0.213



TABLE 7-7 GEOMETRY  $V_b$  RAW and CALCULATED DATA.

1	2	3	4	5	6	7	8	9	10	11	12
Run No	M	$F_n$	Q cfs	$y_n$ cm	$S_n$	$M'$	$\phi_\lambda$	$y_l$ cm	$\frac{h_l}{y_n}$	$\frac{F_n^2}{(-M')}$	K
1	0.2	0.462	2.0	8.76	0.00364	0.241	15.00	23.90	1.72831	3.67779	0.87967
2	0.2	0.368	1.0	6.26	0.00254	0.245	15.00	13.44	1.16774	2.49464	0.87930
3	0.2	0.310	1.0	7.20	0.00138	0.244	15.00	14.22	0.97500	1.61427	1.15494
4	0.2	0.194	1.0	9.84	0.00058	0.238	15.00	14.92	0.51626	0.66266	1.51967
5	0.2	0.096	1.0	15.70	0.00013	0.217	15.00	18.40	0.17197	0.19649	1.73509
6	0.2	0.462	2.0	8.76	0.00364	0.241	30.00	22.54	1.57306	3.67779	0.79641
7	0.2	0.750	2.0	6.34	0.00254	0.245	30.00	13.67	1.15615	9.34820	0.19072
8	0.2	0.310	1.0	7.19	0.00138	0.244	30.00	13.80	0.91933	1.62078	1.08246
9	0.2	0.194	1.0	9.84	0.00058	0.238	30.00	15.79	0.60467	0.66266	1.78335
10	0.2	0.096	1.0	15.70	0.00013	0.217	30.00	18.33	0.16752	0.19649	1.69002
11	0.5	0.467	2.0	8.69	0.00364	0.496	15.00	13.27	0.52704	0.88892	1.01749
12	0.5	0.387	2.0	9.85	0.00234	0.494	15.00	13.59	0.37970	0.61357	1.09851
13	0.5	0.292	2.0	11.89	0.00128	0.492	15.00	14.63	0.23045	0.35263	1.20857



TABLE 7-8 GEOMETRY VI RAW and CALCULATED DATA.

1	2	3	4	5	6	7	8	9	10	11	12	13
Run No.	M	F <sub>n</sub>	Q	y <sub>n</sub> cm	S <sub>n</sub>	M'	y <sub>l</sub> cm	$\frac{h_1^*}{y_n}$	$\frac{F_n^2}{M}$	K	D	$\frac{h_1^*}{y_n} \left( \frac{M'}{F_n} \right)$
1	0.5	0.466	2.0	8.46	0.003750	0.546	12.42	0.46809	0.79310	0.96852	0.71329	0.590
2	0.5	0.389	2.0	9.82	0.002310	0.545	12.98	0.32179	0.50961	1.11036	0.73540	0.631
3	0.5	0.303	2.0	11.59	0.001350	0.543	14.04	0.21139	0.31233	1.24103	0.76066	0.677
4	0.5	0.197	2.0	15.44	0.000610	0.537	17.09	0.10687	0.13493	1.52036	0.80601	0.792
5	0.5	0.099	1.5	15.40	0.000175	0.531	15.87	0.03052	0.03399	1.77568	0.88646	0.898
6	0.3	0.452	1.0	9.60	0.004080	0.547	11.37	1.03036	1.69008	1.10963	0.67701	0.610
7	0.3	0.364	1.0	6.47	0.002650	0.546	11.53	0.78900	1.10151	1.33494	0.69731	0.717
8	0.3	0.280	1.0	7.71	0.001380	0.545	11.99	0.55512	0.65662	1.60710	0.72265	0.845
9	0.3	0.188	1.0	10.56	0.000584	0.541	13.24	0.31610	0.30188	2.03513	0.76245	1.047
10	0.3	0.096	1.0	15.68	0.000132	0.528	18.60	0.18622	0.08623	4.28165	0.83130	2.160
11	0.7	0.498	3.0	10.92	0.003680	0.745	13.17	0.20604	0.44557	0.71653	0.74224	0.462
12	0.7	0.392	3.0	12.80	0.002230	0.744	14.40	0.12500	0.27793	0.76010	0.76680	0.450
13	0.7	0.291	3.0	15.60	0.001220	0.740	16.65	0.06731	0.15487	0.78886	0.79839	0.435
14	0.7	0.190	3.0	20.73	0.000523	0.733	21.36	0.03039	0.06736	0.86489	0.84559	0.451
15	0.7	0.097	2.0	24.82	0.000131	0.725	25.10	0.01128	0.01781	1.25267	0.92688	0.633
16	0.3	0.100	0.7	12.10	0.000133	0.537	13.01	0.07521	0.08778	1.69501	0.83028	0.857
16'	0.3	0.095	0.5	9.41	0.000160	0.542	10.19	0.08289	0.07621	2.15473	0.83642	1.088
16a	0.5	0.190	3.0	20.78	0.005230	0.526	23.84	0.14726	0.12978	2.18955	0.80818	1.135
5a	0.5	0.098	2.0	24.66	0.000131	0.516	26.14	0.06002	0.03592	3.30676	0.88309	1.671
6a	0.5	0.075	2.0	8.60	0.003640	0.544	22.85	1.65698	1.90630	1.61674	0.67141	0.869
7a	0.3	0.394	2.0	9.74	0.007340	0.542	22.54	1.31417	1.32619	1.86779	0.68843	0.991
8a	0.3	0.296	2.0	11.78	0.001280	0.538	23.12	0.96265	0.76689	2.40901	0.71495	1.255
9a	0.3	0.192	2.0	15.70	0.000960	0.528	26.41	0.68217	0.34374	3.88568	0.75565	1.985
10a	0.3	0.096	1.0	15.68	0.000535	0.528	18.60	0.18622	0.08623	4.28165	0.83130	2.160
10b	0.3	0.096	0.7	12.94	0.000147	0.535	11.54	0.12365	0.08262	2.96521	0.83376	1.497
16a	0.7	0.095	3.0	33.03	0.000125	0.705	33.77	0.02240	0.01800	2.46496	0.92622	1.245
17a	0.7	0.167	3.8	28.67	0.000287	0.717	29.68	0.03523	0.04206	1.63389	0.87352	0.838
18a	0.7	0.080	2.1	28.77	0.000081	0.716	29.06	0.01008	0.01251	1.59942	0.94976	0.806
4b	0.5	0.201	3.0	15.89	0.005110	0.528	22.84	0.14832	0.14517	1.96248	0.80196	1.022





TABLE 7-9 GEOMETRY VII RAW and CALCULATED DATA.

Run No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
		$K$	$F_n$	$Q$	$y_n$ cm	$S_n$	$M'$	$\beta$	$y_i$ cm	$\frac{h_n^*}{y_n}$	$(\frac{F_n^2}{M'})$	$K$	$D$	$\frac{h_n^*}{y_n} (\frac{M'}{F_n})^2$
1	0.35		C.447	1.0	5.64	C.004100	C.329	C.50	12.22	1.16667	1.84420	6.41940	0.39976	0.633
2	0.35		C.355	1.0	6.58	C.002540	C.318	C.50	12.39	0.88298	1.23920	5.36265	0.40714	0.713
3	0.35		C.278	1.0	7.74	C.001380	C.310	C.50	12.67	0.63695	0.80499	4.43386	0.41530	0.791
4	0.35		C.187	1.0	10.08	C.000584	C.294	C.50	13.83	0.37202	0.40494	3.55361	0.42865	0.920
5	0.35		C.092	0.7	15.73	C.000124	C.271	C.50	14.26	0.12019	0.11561	2.63145	0.45407	1.040
6	0.35		C.475	2.0	8.59	C.003640	C.325	C.30	19.49	1.26892	2.13313	6.65206	0.42191	0.595
7	0.35		C.391	2.0	9.79	C.002340	C.318	C.30	19.70	1.01226	1.50498	5.81817	0.42477	0.673
8	0.35		C.278	1.0	7.73	C.001380	C.328	C.30	12.24	0.58344	0.20292	4.25285	0.42930	0.809
9	0.35		C.191	1.0	9.94	C.000560	C.320	C.30	13.28	0.33602	0.35711	3.45920	0.43415	0.941
10	0.35		C.096	1.0	18.71	C.000132	C.286	C.30	17.50	0.11394	0.11296	2.52687	0.44222	1.009
11	0.35		C.478	2.0	8.56	C.003640	C.326	C.30	17.68	1.06342	2.15100	6.64210	0.45525	0.495
12	0.35		C.397	2.0	9.68	C.002340	C.325	C.30	17.97	0.85640	1.49063	4.27092	0.46344	0.575
13	0.35		C.345	3.0	15.49	C.001400	C.294	C.30	25.26	0.63073	1.00092	3.52401	0.61259	0.630
14	0.35		C.193	2.0	15.67	C.000560	C.316	C.30	20.49	0.30759	0.37354	2.90076	0.56170	0.823
15	0.35		C.106	1.0	15.71	C.000132	C.327	C.30	17.04	0.03466	0.08643	2.32732	0.49382	0.979
16	0.50		C.478	2.7	10.59	C.003410	C.445	C.50	18.59	0.75543	1.15158	4.53756	0.40851	0.656
17	0.50		C.388	2.0	9.83	C.002340	C.452	C.50	15.02	0.52798	0.73655	3.67511	0.41700	0.717
18	0.50		C.291	2.0	11.91	C.001280	C.436	C.50	15.92	0.33669	0.44504	2.88341	0.42678	0.757
19	0.50		C.191	1.0	18.34	C.000584	C.428	C.50	11.46	0.15292	0.19860	2.11948	0.44291	0.770
20	0.50		C.101	1.0	18.22	C.000132	C.412	C.50	16.03	0.05322	0.05970	2.00016	0.46809	0.692
21	0.50		C.490	3.8	13.02	C.003280	C.460	C.30	21.16	0.62919	1.13661	3.32239	0.42618	0.550
22	0.50		C.392	3.8	15.12	C.002090	C.449	C.30	23.22	0.53371	0.76175	3.64584	0.42892	0.703
23	0.50		C.295	3.8	18.26	C.001150	C.435	C.30	24.83	0.35980	0.46076	3.08060	0.43238	0.781
24	0.50		C.199	2.0	15.33	C.000560	C.450	C.30	17.67	0.15264	0.19636	2.14544	0.43832	0.777
25	0.50		C.100	1.0	15.27	C.000132	C.449	C.30	15.93	0.04322	0.04978	1.91126	0.44895	0.868
26	0.50		C.490	3.8	13.02	C.003280	C.470	C.30	22.56	0.73372	1.08644	4.58154	0.46173	0.674
27	0.50		C.392	3.8	15.12	C.002090	C.472	C.30	21.96	0.45238	0.68786	3.07178	0.59270	0.658
28	0.50		C.295	3.8	18.26	C.001150	C.468	C.30	23.33	0.27768	0.39723	2.44863	0.56475	0.699
29	0.50		C.195	3.8	24.08	C.000501	C.453	C.30	27.24	0.13123	0.18486	1.88590	0.52798	0.710
30	0.50		C.097	3.0	32.50	C.000125	C.422	C.30	33.31	0.02492	0.05260	1.00630	0.47270	0.474
31	0.75		C.496	3.0	10.94	C.003680	C.697	C.50	13.51	0.23492	0.50599	1.72257	0.42426	0.464
32	0.75		C.295	2.0	11.62	C.002230	C.690	C.50	14.39	0.14025	0.33683	1.25428	0.43228	0.416
33	0.75		C.496	3.0	12.80	C.001280	C.694	C.50	12.64	0.07119	0.18115	0.98696	0.44479	0.393
34	0.75		C.195	2.0	15.56	C.000131	C.670	C.50	16.06	0.03213	0.08477	0.84279	0.46060	0.379
35	0.75		C.101	2.0	24.13	C.000131	C.615	C.50	24.44	0.01285	0.02696	0.98553	0.4779	0.477
36	0.75		C.496	3.0	10.94	C.003680	C.721	C.30	12.88	0.17733	0.47289	1.28077	0.43220	0.375
37	0.75		C.403	3.0	18.57	C.002230	C.718	C.30	14.14	0.12490	0.31501	1.16752	0.53502	0.396
38	0.75		C.295	2.0	11.80	C.001280	C.715	C.30	12.51	0.06017	0.17066	0.86852	0.43931	0.353
39	0.75		C.195	2.0	15.56	C.000560	C.706	C.30	15.96	0.02571	0.07618	0.74123	0.44502	0.469
40	0.75		C.101	2.0	24.06	C.000131	C.668	C.30	24.32	0.01081	0.02303	0.97040	0.45362	0.337
41	0.75		C.496	3.0	10.94	C.003680	C.729	C.30	12.88	0.17733	0.46321	1.30753	0.57243	0.383
42	0.75		C.402	3.0	12.58	C.002300	C.742	C.30	13.92	0.10652	0.29366	1.03667	0.54993	0.363
43	0.75		C.443	3.0	11.80	C.001280	C.744	C.30	12.41	0.05169	0.35440	0.39313	0.55910	0.146
44	0.75		C.195	2.0	15.54	C.000560	C.744	C.30	15.87	0.02124	0.06896	0.67082	0.48410	0.308
45	0.75		C.101	2.0	24.15	C.000131	C.726	C.30	24.29	0.00390	0.01930	0.61519	0.43277	0.300



TABLE VIII - RAW DATA - AREA OF YEA CANTACTA - BACKWATER AND PROFILE

Run No. = 2									
Q	=	4.74	cfs.						
V <sub>1</sub>	=	30.24	cm.						
V <sub>2</sub>	=	0.0	cm.						
N	=	b/B	= 0.30						
Model Sta.	=	30.00	ft.						
A <sub>0</sub>	=	0.884	sq. ft.						
b <sub>0</sub>	=	0.0	ft.						
Run No. = 3									
Q	=	4.74	cfs.						
V <sub>1</sub>	=	30.24	cm.						
V <sub>2</sub>	=	0.0	cm.						
N	=	b/B	= 0.30						
Model Sta.	=	30.00	ft.						
A <sub>0</sub>	=	0.884	sq. ft.						
b <sub>0</sub>	=	0.0	ft.						
Run No. = 4									
Q	=	3.735	cfs.						
V <sub>1</sub>	=	30.24	cm.						
V <sub>2</sub>	=	0.0	cm.						
N	=	b/B	= 0.30						
Model Sta.	=	30.00	ft.						
A <sub>0</sub>	=	0.884	sq. ft.						
b <sub>0</sub>	=	0.0	ft.						
Run No. = 5									
Q	=	3.98	cfs.						
V <sub>1</sub>	=	30.24	cm.						
V <sub>2</sub>	=	14.05	cm.						
N	=	b/B	= 0.30						
Model Sta.	=	30.00	ft.						
A <sub>0</sub>	=	0.884	sq. ft.						
b <sub>0</sub>	=	0.0	ft.						
Run No. = 6									
Q	=	3.40	cfs.						
V <sub>1</sub>	=	30.24	cm.						
V <sub>2</sub>	=	0.0	cm.						
N	=	b/B	= 0.30						
Model Sta.	=	30.00	ft.						
A <sub>0</sub>	=	0.884	sq. ft.						
b <sub>0</sub>	=	0.0	ft.						
Run No. = 7									
Q	=	3.18	cfs.						
V <sub>1</sub>	=	30.24	cm.						
V <sub>2</sub>	=	0.0	cm.						
N	=	b/B	= 0.30						
Model Sta.	=	30.00	ft.						
A <sub>0</sub>	=	0.884	sq. ft.						
b <sub>0</sub>	=	0.0	ft.						
Run No. = 8									
Q	=	2.89	cfs.						
V <sub>1</sub>	=	27.83	cm.						
V <sub>2</sub>	=	0.30	cm.						
N	=	b/B	= 0.30						
Model Sta.	=	30.00	ft.						
A <sub>0</sub>	=	0.884	sq. ft.						
b <sub>0</sub>	=	0.0	ft.						
Run No. = 10									
Q	=	2.535	cfs.						
V <sub>1</sub>	=	24.13	cm.						
V <sub>2</sub>	=	0.30	cm.						
N	=	b/B	= 0.30						
Model Sta.	=	30.00	ft.						
A <sub>0</sub>	=	0.884	sq. ft.						
b <sub>0</sub>	=	0.0	ft.						























TABLE 87 - RAW DATA - AREA OF VENA CONTRACTA - BACKWATER AND PROFILE

Run No. = 43									
Q	=	1.872 cfs.							
$V_1$	=	23.43 cm.							
$V_2$	=	0.83 cm.							
$M = b/B$	=	0.25							
Model Sta.	=	30.00 ft.							
$N_1$	=	0.014 sq. ft.							
$N_2$	=	0.0							
$N_3$	=	0.0							
Run No. = 44									
Q	=	1.742 cfs.							
$V_1$	=	20.88 cm.							
$V_2$	=	0.83 cm.							
$M = b/B$	=	0.25							
Model Sta.	=	30.00 ft.							
$N_1$	=	0.014 sq. ft.							
$N_2$	=	0.0							
$N_3$	=	0.0							
Run No. = 45									
Q	=	3.70 cfs.							
$V_1$	=	55.65 cm.							
$V_2$	=	0.00 cm.							
$M = b/B$	=	0.25							
Model Sta.	=	30.00 ft.							
$N_1$	=	0.014 sq. ft.							
$N_2$	=	0.0							
$N_3$	=	0.0							
Run No. = 46									
Q	=	2.835 cfs.							
$V_1$	=	55.65 cm.							
$V_2$	=	0.00 cm.							
$M = b/B$	=	0.25							
Model Sta.	=	30.00 ft.							
$N_1$	=	0.014 sq. ft.							
$N_2$	=	0.0							
$N_3$	=	0.0							
Run No. = 47									
Q	=	2.515 cfs.							
$V_1$	=	23.43 cm.							
$V_2$	=	2.08 cm.							
$M = b/B$	=	0.25							
Model Sta.	=	30.00 ft.							
$N_1$	=	0.014 sq. ft.							
$N_2$	=	0.0							
$N_3$	=	0.0							
Run No. = 48									
Q	=	2.112 cfs.							
$V_1$	=	23.43 cm.							
$V_2$	=	2.33 cm.							
$M = b/B$	=	0.250							
Model Sta.	=	30.00 ft.							
$N_1$	=	0.014 sq. ft.							
$N_2$	=	0.0							
$N_3$	=	0.0							
Run No. = 49									
Q	=	1.820 cfs.							
$V_1$	=	23.43 cm.							
$V_2$	=	2.55 cm.							
$M = b/B$	=	0.25							
Model Sta.	=	30.00 ft.							
$N_1$	=	0.014 sq. ft.							
$N_2$	=	0.0							
$N_3$	=	0.0							
Run No. = 51									
Q	=	2.552 cfs.							
$V_1$	=	23.43 cm.							
$V_2$	=	70.0 cm.							
$M = b/B$	=	0.20							
Model Sta.	=	30.00 ft.							
$N_1$	=	0.014 sq. ft.							
$N_2$	=	0.0							
$N_3$	=	0.0							









TABLE 8-4. RAW DATA - AREA OF VENA CONTRACTA - BACKWATER AND PROFILE

Run No. = 60									
Q	=	1.62 cfs.							
Y <sub>1</sub>	=	29.65 cm.							
Y <sub>2</sub>	=	29.65 cm.							
H <sup>2</sup> = b/B	=	0.20							
Model Sta.	=	30.00 ft.							
L/b	=	0.0							
Profile of Jet									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.384	1.057	0.389	30.18	0.389	1.055	0.00	30.18	0.00
30.30	0.269	1.10	0.177	30.30	0.362	1.10	0.173	30.30	0.356
30.40	0.348	1.20	0.292	30.40	0.360	1.20	0.287	30.40	1.10
30.50	0.368	1.20	0.364	30.50	0.360	1.20	0.364	30.50	1.20
30.60	0.392	1.40	0.384	30.60	0.300	1.40	0.381	30.60	0.299
31.00	0.217	1.50	0.210	31.00	0.205	1.50	0.205	31.00	0.298
31.50	0.145	1.60	0.379	31.50	0.141	1.60	0.378	31.50	0.248
32.00	0.112	1.80	0.266	32.00	0.102	1.80	0.264	32.00	0.192
								31.00	1.50
								31.50	1.60
								32.00	0.125
								32.00	0.092
								32.00	1.80
								32.00	0.270
								32.00	1.90
								32.00	0.136
								32.00	1.932
								32.00	0.00
Cross-section									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.00			30.18	0.00			30.18	0.00
30.30	0.177			30.30	0.362			30.30	0.356
30.40	0.292			30.40	0.360			30.40	1.10
30.50	0.364			30.50	0.360			30.50	1.20
30.60	0.384			30.60	0.300			30.60	0.299
31.00	0.210			31.00	0.205			31.00	0.298
31.50	0.379			31.50	0.141			31.50	0.248
32.00	0.266			32.00	0.102			32.00	0.192
								31.00	1.50
								31.50	1.60
								32.00	0.125
								32.00	0.092
								32.00	1.80
								32.00	0.270
								32.00	1.90
								32.00	0.136
								32.00	1.932
								32.00	0.00
Profile of Jet									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.00			30.18	0.00			30.18	0.00
30.30	0.177			30.30	0.362			30.30	0.356
30.40	0.292			30.40	0.360			30.40	1.10
30.50	0.364			30.50	0.360			30.50	1.20
30.60	0.384			30.60	0.300			30.60	0.299
31.00	0.210			31.00	0.205			31.00	0.298
31.50	0.379			31.50	0.141			31.50	0.248
32.00	0.266			32.00	0.102			32.00	0.192
								31.00	1.50
								31.50	1.60
								32.00	0.125
								32.00	0.092
								32.00	1.80
								32.00	0.270
								32.00	1.90
								32.00	0.136
								32.00	1.932
								32.00	0.00
Cross-section									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.00			30.18	0.00			30.18	0.00
30.30	0.177			30.30	0.362			30.30	0.356
30.40	0.292			30.40	0.360			30.40	1.10
30.50	0.364			30.50	0.360			30.50	1.20
30.60	0.384			30.60	0.300			30.60	0.299
31.00	0.210			31.00	0.205			31.00	0.298
31.50	0.379			31.50	0.141			31.50	0.248
32.00	0.266			32.00	0.102			32.00	0.192
								31.00	1.50
								31.50	1.60
								32.00	0.125
								32.00	0.092
								32.00	1.80
								32.00	0.270
								32.00	1.90
								32.00	0.136
								32.00	1.932
								32.00	0.00
Profile of Jet									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.00			30.18	0.00			30.18	0.00
30.30	0.177			30.30	0.362			30.30	0.356
30.40	0.292			30.40	0.360			30.40	1.10
30.50	0.364			30.50	0.360			30.50	1.20
30.60	0.384			30.60	0.300			30.60	0.299
31.00	0.210			31.00	0.205			31.00	0.298
31.50	0.379			31.50	0.141			31.50	0.248
32.00	0.266			32.00	0.102			32.00	0.192
								31.00	1.50
								31.50	1.60
								32.00	0.125
								32.00	0.092
								32.00	1.80
								32.00	0.270
								32.00	1.90
								32.00	0.136
								32.00	1.932
								32.00	0.00
Cross-section									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.00			30.18	0.00			30.18	0.00
30.30	0.177			30.30	0.362			30.30	0.356
30.40	0.292			30.40	0.360			30.40	1.10
30.50	0.364			30.50	0.360			30.50	1.20
30.60	0.384			30.60	0.300			30.60	0.299
31.00	0.210			31.00	0.205			31.00	0.298
31.50	0.379			31.50	0.141			31.50	0.248
32.00	0.266			32.00	0.102			32.00	0.192
								31.00	1.50
								31.50	1.60
								32.00	0.125
								32.00	0.092
								32.00	1.80
								32.00	0.270
								32.00	1.90
								32.00	0.136
								32.00	1.932
								32.00	0.00
Profile of Jet									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.00			30.18	0.00			30.18	0.00
30.30	0.177			30.30	0.362			30.30	0.356
30.40	0.292			30.40	0.360			30.40	1.10
30.50	0.364			30.50	0.360			30.50	1.20
30.60	0.384			30.60	0.300			30.60	0.299
31.00	0.210			31.00	0.205			31.00	0.298
31.50	0.379			31.50	0.141			31.50	0.248
32.00	0.266			32.00	0.102			32.00	0.192
								31.00	1.50
								31.50	1.60
								32.00	0.125
								32.00	0.092
								32.00	1.80
								32.00	0.270
								32.00	1.90
								32.00	0.136
								32.00	1.932
								32.00	0.00
Cross-section									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.00			30.18	0.00			30.18	0.00
30.30	0.177			30.30	0.362			30.30	0.356
30.40	0.292			30.40	0.360			30.40	1.10
30.50	0.364			30.50	0.360			30.50	1.20
30.60	0.384			30.60	0.300			30.60	0.299
31.00	0.210			31.00	0.205			31.00	0.298
31.50	0.379			31.50	0.141			31.50	0.248
32.00	0.266			32.00	0.102			32.00	0.192
								31.00	1.50
								31.50	1.60
								32.00	0.125
								32.00	0.092
								32.00	1.80
								32.00	0.270
								32.00	1.90
								32.00	0.136
								32.00	1.932
								32.00	0.00
Profile of Jet									
Sta.	ft.	ft.	ft.	Sta.	ft.	ft.	ft.	Sta.	ft.
Traverse 30.11				Traverse 30.11				Traverse 30.11	
30.18	0.00			30.18	0.00			30.18	0.00
30.30	0.177			30.30	0.362			30.30	0.356
30.40	0.292			30.40	0.360			30.40	1.10
30.50	0.364			30.50	0.360			30.50	1.20
30.60	0.384			30.60	0.300			30.60	0.299
31.00	0.210			31.00	0.205			31.00	0.298
31.50	0.379			31.50	0.141			31.50	0.248
32.00	0.266			32.00	0.102			32.00	0.192
								31	













TABLE 8-2 BAW DATA - SUMMERGED TESTS

- 135 -									
Run No.	Geometry	Depth	Sta.	L	Depth	Sta.	L	Depth	Sta.
10	n	0.0110	42.64	10	0.0110	42.64	10	0.0110	42.64
15	q	-2.0 cfs.	"	15	-2.0 cfs.	"	15	-2.0 cfs.	"
20	F <sub>n</sub>	-0.80 ft.	"	20	-0.80 ft.	"	20	-0.80 ft.	"
25	F <sub>n</sub>	-0.10	"	25	-0.10	"	25	-0.10	"
30	S <sub>n</sub>	0.0000255	"	30	0.0000255	"	30	0.0000255	"
35	M <sub>2</sub> /B	-0.20	"	35	-0.20	"	35	-0.20	"
40	L/b	0.25	"	40	0.25	"	40	0.25	"
45	Temp.	-72° F	"	45	-72° F	"	45	-72° F	"
50	Model Sta.	-30.00	"	50	-30.00	"	50	-30.00	"
55	Y <sub>1</sub>	-21.64 cm.	"	55	-21.64 cm.	"	55	-21.64 cm.	"
60	Y <sub>2</sub>	-19.55 cm.	"	60	-19.55 cm.	"	60	-19.55 cm.	"
65	N	-1.0	"	65	-1.0	"	65	-1.0	"
70	Q	2	"	70	2	"	70	2	"
75	Q	2	"	75	2	"	75	2	"
80	Q	2	"	80	2	"	80	2	"
85	Q	2	"	85	2	"	85	2	"
90	Q	2	"	90	2	"	90	2	"
95	Q	2	"	95	2	"	95	2	"
100	Q	2	"	100	2	"	100	2	"
105	Q	2	"	105	2	"	105	2	"
110	Q	2	"	110	2	"	110	2	"
115	Q	2	"	115	2	"	115	2	"
120	Q	2	"	120	2	"	120	2	"
125	Q	2	"	125	2	"	125	2	"
130	Q	2	"	130	2	"	130	2	"
135	Q	2	"	135	2	"	135	2	"
140	Q	2	"	140	2	"	140	2	"
145	Q	2	"	145	2	"	145	2	"
150	Q	2	"	150	2	"	150	2	"
155	Q	2	"	155	2	"	155	2	"
160	Q	2	"	160	2	"	160	2	"
165	Q	2	"	165	2	"	165	2	"
170	Q	2	"	170	2	"	170	2	"
175	Q	2	"	175	2	"	175	2	"
180	Q	2	"	180	2	"	180	2	"
185	Q	2	"	185	2	"	185	2	"
190	Q	2	"	190	2	"	190	2	"
195	Q	2	"	195	2	"	195	2	"
200	Q	2	"	200	2	"	200	2	"
205	Q	2	"	205	2	"	205	2	"
210	Q	2	"	210	2	"	210	2	"
215	Q	2	"	215	2	"	215	2	"
220	Q	2	"	220	2	"	220	2	"
225	Q	2	"	225	2	"	225	2	"
230	Q	2	"	230	2	"	230	2	"
235	Q	2	"	235	2	"	235	2	"
240	Q	2	"	240	2	"	240	2	"
245	Q	2	"	245	2	"	245	2	"
250	Q	2	"	250	2	"	250	2	"
255	Q	2	"	255	2	"	255	2	"
260	Q	2	"	260	2	"	260	2	"
265	Q	2	"	265	2	"	265	2	"
270	Q	2	"	270	2	"	270	2	"
275	Q	2	"	275	2	"	275	2	"
280	Q	2	"	280	2	"	280	2	"
285	Q	2	"	285	2	"	285	2	"
290	Q	2	"	290	2	"	290	2	"
295	Q	2	"	295	2	"	295	2	"
300	Q	2	"	300	2	"	300	2	"
305	Q	2	"	305	2	"	305	2	"
310	Q	2	"	310	2	"	310	2	"
315	Q	2	"	315	2	"	315	2	"
320	Q	2	"	320	2	"	320	2	"
325	Q	2	"	325	2	"	325	2	"
330	Q	2	"	330	2	"	330	2	"
335	Q	2	"	335	2	"	335	2	"
340	Q	2	"	340	2	"	340	2	"
345	Q	2	"	345	2	"	345	2	"
350	Q	2	"	350	2	"	350	2	"
355	Q	2	"	355	2	"	355	2	"
360	Q	2	"	360	2	"	360	2	"
365	Q	2	"	365	2	"	365	2	"
370	Q	2	"	370	2	"	370	2	"
375	Q	2	"	375	2	"	375	2	"
380	Q	2	"	380	2	"	380	2	"
385	Q	2	"	385	2	"	385	2	"
390	Q	2	"	390	2	"	390	2	"
395	Q	2	"	395	2	"	395	2	"
400	Q	2	"	400	2	"	400	2	"
405	Q	2	"	405	2	"	405	2	"
410	Q	2	"	410	2	"	410	2	"
415	Q	2	"	415	2	"	415	2	"
420	Q	2	"	420	2	"	420	2	"
425	Q	2	"	425	2	"	425	2	"
430	Q	2	"	430	2	"	430	2	"
435	Q	2	"	435	2	"	435	2	"
440	Q	2	"	440	2	"	440	2	"
445	Q	2	"	445	2	"	445	2	"
450	Q	2	"	450	2	"	450	2	"
455	Q	2	"	455	2	"	455	2	"
460	Q	2	"	460	2	"	460	2	"
465	Q	2	"	465	2	"	465	2	"
470	Q	2	"	470	2	"	470	2	"
475	Q	2	"	475	2	"	475	2	"
480	Q	2	"	480	2	"	480	2	"
485	Q	2	"	485	2	"	485	2	"
490	Q	2	"	490	2	"	490	2	"
495	Q	2	"	495	2	"	495	2	"
500	Q	2	"	500	2	"	500	2	"
505	Q	2	"	505	2	"	505	2	"
510	Q	2	"	510	2	"	510	2	"
515	Q	2	"	515	2	"	515	2	"
520	Q	2	"	520	2	"	520	2	"
525	Q	2	"	525	2	"	525	2	"
530	Q	2	"	530	2	"	530	2	"
535	Q	2	"	535	2	"	535	2	"
540	Q	2	"	540	2	"	540	2	"
545	Q	2	"	545	2	"	545	2	"
550	Q	2	"	550	2	"	550	2	"
555	Q	2	"	555	2	"	555	2	"
560	Q	2	"	560	2	"	560	2	"
565	Q	2	"	565	2	"	565	2	"
570	Q	2	"	570	2	"	570	2	"
575	Q	2	"	575	2	"	575	2	"
580	Q	2	"	580	2	"	580	2	"
585	Q	2	"	585	2	"	585	2	"
590	Q	2	"	590	2	"	590	2	"
595	Q	2	"	595	2	"	595	2	"
600	Q	2	"	600	2	"	600	2	"
605	Q	2	"	605	2	"	605	2	"
610	Q	2	"	610	2	"	610	2	"
615	Q	2	"	615	2	"	615	2	"
620	Q	2	"	620	2	"	620	2	"
625	Q	2	"	625	2	"	625	2	"
630	Q	2	"	630	2	"	630	2	"
635	Q	2	"	635	2	"	635	2	"
640	Q	2	"	640	2	"	640	2	"
645	Q	2	"	645	2	"	645	2	"
650	Q	2	"	650	2	"	650	2	"
655	Q	2	"	655	2	"	655	2	"
660	Q	2	"	660	2	"	660	2	"
665	Q	2	"	665	2	"	665	2	"
670	Q	2	"	670	2	"	670	2	"
675	Q	2	"	675	2	"	675	2	"
680	Q	2	"	680	2	"	680	2	"
685	Q	2	"	685	2	"	685	2	"
690	Q	2	"	690	2	"	690	2	"
695	Q	2	"	695	2	"	695	2	"
700	Q	2	"	700	2	"	700	2	"
705	Q	2	"	705	2	"	705	2	"
710	Q	2	"	710	2	"	710	2	"
715	Q	2	"	715	2	"	715	2	"
720	Q	2	"	720	2	"	720	2	"
725	Q	2	"	725	2	"	725	2	"
730	Q	2	"	730	2	"	730	2	"
735	Q	2	"	735	2	"	735	2	"
740	Q	2	"	740	2	"	740	2	"
745	Q	2	"	745	2	"	745	2	"
750	Q	2	"	750	2	"	750	2	"
755	Q	2	"	755	2	"	755	2	"
760	Q	2	"	760	2	"	760	2	"
765	Q	2	"	765	2	"	765	2	"
770	Q	2	"	770	2	"	770	2	"
775	Q	2	"	775	2	"	775	2	"
780	Q	2	"	780	2	"	780	2	"
785	Q	2	"	785	2	"	785	2	"
790	Q	2	"	790	2	"	790	2	"
795	Q	2	"	795	2	"	795	2	"
800	Q	2	"	800	2	"	800	2	"
805	Q	2	"	805	2	"	805	2	"
810	Q	2	"	810	2	"	810	2	"
815	Q	2	"	815	2	"	815	2	"
820	Q	2	"	820	2	"	820	2	"
825	Q	2	"	825	2	"	825	2	"
830	Q	2	"	830	2	"	830	2	"
835	Q	2	"	835	2	"	835	2	"
840	Q	2	"	840	2	"	840	2	"
845	Q	2	"	845	2	"	845	2	"
850	Q	2	"	850	2	"	850	2	"
855	Q	2	"	855	2	"	855	2	"
860	Q	2	"	860	2	"	860	2	"
865	Q	2	"	865	2	"	865	2	"
870	Q	2	"	870	2	"	870	2	"
875	Q	2	"	875	2				

























































TABLE 8-4 CALCULATED VALUES - RUN NO. 2 - 140

Run No.	$\Delta$	$q_t$	$c_c$	$c_d$	$c_v$	$\frac{b}{Y_1}$	$Y_n$	$F_n$
2	.635	8.317	.718	.570	.862	.901	.435	.587
3	.632	7.291	.715	.574	.812	1.126	.393	.583
4	.608	8.737	.710	.552	.798	1.257	.372	.580
5	.617	6.585	.698	.544	.785	1.293	.364	.579
6	.624	6.229	.705	.542	.775	1.400	.352	.578
7	.614	5.897	.694	.540	.771	1.500	.338	.576
8	.609	5.493	.711	.526	.752	1.640	.318	.573
9	.654	5.198	.740	.520	.744	1.759	.305	.570
10	.641	4.917	.726	.515	.736	1.870	.293	.569
11	.594	8.265	.671	.570	.844	.919	.433	.587
12	.604	7.732	.682	.550	.806	1.110	.392	.583
13	.614	6.687	.694	.556	.800	1.267	.374	.580
14	.622	6.163	.704	.540	.771	1.418	.348	.577
15	.623	5.450	.705	.529	.756	1.597	.317	.572
16	.515	7.732	.711	.526	.785	.800	.401	.584
17	.488	6.475	.674	.370	.518	.956	.372	.580
18	.490	6.371	.676	.394	.546	.980	.367	.580
19	.491	6.148	.677	.440	.613	1.025	.357	.578
20	.500	5.563	.690	.623	.902	1.208	.332	.575
21	.505	5.291	.697	.747	1.040	1.297	.321	.573
22	.506	5.000	.700	.917	1.274	1.400	.307	.571
23	.510	4.990	.705	.960	1.371	1.420	.306	.571
24	.522	4.668	.721	1.240	1.671	1.530	.291	.568
25	.524	4.688	.723	1.386	1.915	1.610	.282	.567
26	.525	4.133	.725	1.949	2.780	1.780	.267	.560
27	.511	4.626	.706	1.257	1.793	1.550	.293	.569
28	.508	4.920	.701	1.680	1.435	1.430	.309	.571
29	.501	5.252	.692	.784	1.162	1.310	.323	.573
30	.496	5.701	.685	.578	0.843	1.165	.341	.576
31	.488	6.283	.674	.408	0.695	1.010	.363	.579
32	.411	6.240	.670	.591	.883	.690	.371	.580
33	.410	5.939	.669	.589	.879	.750	.358	.578
34	.417	5.729	.679	.595	.869	.797	.353	.578
35	.425	5.308	.693	.584	.872	.900	.334	.575
36	.413	5.115	.672	.588	.878	.945	.327	.574
37	.421	4.768	.685	.587	.876	1.000	.320	.571
38	.422	4.716	.686	.590	.872	1.082	.310	.571
39	.427	4.445	.695	.567	.845	1.182	.291	.568
40	.429	4.221	.699	.565	.816	1.273	.282	.566
41	.435	3.899	.709	.560	.804	1.420	.266	.563
42	.434	3.653	.707	.555	.794	1.549	.255	.561
43	.433	3.511	.705	.549	.784	1.638	.246	.558
44	.432	3.188	.701	.540	.768	1.845	.234	.551
45	.412	6.256	.670	.591	.883	.686	.371	.583
46	.414	4.842	.674	.585	.868	1.040	.314	.572
47	.415	4.374	.676	.575	.839	1.410	.291	.568
48	.430	3.741	.700	.565	.807	1.500	.261	.562
49	.434	3.273	.706	.556	.795	1.773	.230	.556
51	.261	4.256	.664	.600	.896	.518	.294	.569
52	.262	4.097	.665	.598	.893	.545	.286	.567
53	.262	3.868	.666	.592	.884	.601	.275	.565
54	.263	3.700	.667	.587	.875	.650	.266	.563
55	.263	3.560	.667	.595	.889	.695	.262	.562
56	.267	3.388	.678	.583	.870	.725	.251	.559
57	.263	3.286	.668	.587	.873	.792	.247	.558
58	.263	3.088	.668	.583	.869	.879	.236	.556
59	.263	2.964	.668	.590	.881	.937	.232	.555
60	.263	2.792	.668	.580	.866	1.030	.221	.551
61	.264	2.706	.670	.580	.861	1.080	.212	.550
62	.273	2.654	.693	.578	.843	1.112	.214	.550
63	.276	2.562	.702	.580	.841	1.215	.207	.548
64	.252	2.282	.639	.575	.826	1.380	.194	.544
65	.275	2.204	.698	.572	.821	1.448	.208	.551
66	.277	2.093	.705	.574	.820	1.548	.184	.540
67	.277	1.929	.705	.560	.801	1.710	.172	.536

Run No.	K	$11^*$	$\frac{h_1}{Y_n}$	$\left(\frac{F_n}{M^2}\right)^2$	$\frac{Q}{gY_n^2}$	$\frac{Y_1}{Y_n}$	$\frac{Y_1}{Y_2}$	$q_t$	$c_d$
102	2.132	.141	.637	.594	.253	1.145	2.290	1.395	5.624
103	1.886	.171	.385	.405	.199	.878	1.762	1.272	5.789
104	1.955	.203	.282	.286	.160	.745	1.480	1.166	6.417
105	2.232	.104	1.191	1.062	.353	1.670	3.330	1.521	3.874
106	2.210	.162	.685	.436	.202	.905	1.820	1.219	4.647
107	2.230	.196	.335	.297	.159	.737	1.479	1.109	5.124
108	1.960	.234	.208	.210	.148	.612	1.227	1.030	5.522
109	2.201	.141	.497	.593	.202	1.160	2.308	1.400	5.447
110	3.004	.171	.612	.405	.159	1.020	2.050	1.274	6.397
111	2.146	.203	.310	.286	.128	.764	1.527	1.168	6.517
112	2.020	.120	1.957	1.923	.441	1.940	3.882	1.321	4.220
113	2.095	.188	.838	.789	.253	.966	1.934	1.067	4.854
114	1.862	.227	.510	.538	.199	.720	1.443	.969	5.038
115	1.907	.271	.370	.380	.160	.600	1.201	.888	5.128
116	2.188	.159	1.062	.961	.251	1.280	2.562	1.342	5.725
117	2.283	.192	.798	.655	.208	.992	1.989	1.131	6.272
118	2.190	.229	.515	.663	.192	.785	1.771	1.037	6.649
119	2.066	.174	.844	.807	.278	1.150	2.300	1.250	6.889
120	2.807	.207	.594	.418	.224	.912	1.825	1.140	7.375
121	2.045	.120	1.981	1.923	.441	1.960	3.920	1.321	4.246
122	2.171	.188	.869	.789	.253	.982	1.965	1.067	4.906
123	2.239	.227	.613	.538	.199	.769	1.542	.969	5.282
124	2.040	.171	.396	.280	.160	.610	1.222	.888	5.510
125		.156			.441	1.930	3.860	1.080	4.214
126		.228			.253	.960	1.925	.864	4.840
127		.277			.199	.734	1.471	.786	5.106
128		.269			.160	.573	1.148	.700	5.225
129	2.121	.194	1.263	1.171	.303	1.156	2.301	1.020	5.434
130	2.178	.234	.889	.799	.238	.874	1.755	.928	5.771
131	2.097	.279	.607	.564	.192	.684	1.367	.849	6.010
132	2.040	.173	1.479	1.429	.394	1.410	2.820	1.138	6.136
133	2.141	.210	1.043	.974	.278	1.065	2.135	1.035	6.565
134	2.065	.250	.727	.688	.224	.820	1.639	.949	6.852
171	1.886	.140	1.100	1.154	.354	1.480			
180	2.211	.256	1.694	1.277	.256	.830			
191	2.204	.170	1.565	1.401	.354	1.490			
195	1.878	.100	.953	1.011	.353	1.560			
136	1.617	.100	.821	1.011	.353	1.455			
137	1.555	.100	.790	1.011	.353	1.430			
138	1.347	.100	.684	1.011	.353	1.348			
139	2.436	.154	.544	.415	.202	.988			
140	1.865	.154	.390	.415	.202	.890			



TABLE 8-5- CALCULATED VALUES - RUN NO. 141 - 306

Run No.	K	M	$\frac{h_1}{Y_1}$	$\left(\frac{F}{M}\right)^2$	$\frac{1}{g^2 b^2/2}$	$\frac{Y_1}{b}$	Run No.	K	M	$\frac{h_1}{Y_1}$	$\left(\frac{F}{M}\right)^2$	$\frac{1}{g^2 b^2/2}$	$\frac{Y_1}{b}$
141	1.527	.154	.390	.415	.202	.843	222	1.580	.252	.285	.353	.253	.605
142	1.466	.154	.306	.415	.202	.835	223	1.596	.252	.285	.353	.253	.592
143	1.431	.223	.144	.200	.128	.610	224	1.398	.158	1.149	1.617	.253	1.075
144	1.333	.223	.134	.200	.128	.600	225	1.240	.158	1.021	1.617	.253	1.010
145	1.227	.223	.123	.200	.128	.600	226	1.079	.158	.890	1.617	.253	.943
146	.893	.223	.090	.200	.128	.588	227	1.073	.135	1.177	2.159	.441	1.270
147	2.430	.134	.688	.563	.253	1.100	228	1.036	.135	1.137	2.159	.441	1.250
148	1.577	.134	.447	.563	.253	1.065	229	1.419	.211	.465	.886	.253	.584
149	1.503	.134	.427	.563	.253	1.050	230	1.311	.211	.465	.886	.253	.584
150	1.603	.134	.398	.563	.253	1.030	231	1.059	.304	.234	.427	.160	.480
151	1.891	.113	1.719	1.804	.441	1.900	232	.854	.100	.333	1.011	.253	1.067
152	1.788	.113	1.625	1.804	.441	1.839	233	.251	.223	.225	.200	.128	.504
153	1.684	.113	1.531	1.804	.441	1.771	234	.694	.100	.333	1.011	.253	1.067
154	1.602	.113	1.457	1.804	.441	1.718	235	.159	.223	.217	.200	.128	.512
155	1.941	.176	.728	.740	.253	.980	236	.786	.100	.400	1.011	.253	1.120
156	1.672	.176	.647	.740	.253	.910	237	.222	.223	.222	.200	.128	.524
157	1.523	.176	.572	.740	.253	.880	238	.458	.276	.104	.749	.529	1.460
158	1.283	.176	.483	.740	.253	.823	239	.226	.171	.040	.345	.192	.721
159	1.440	.254	.262	.356	.160	.589	240	.537	.076	.713	1.749	.529	1.530
160	1.000	.254	.182	.356	.160	.523	241	.307	.171	.054	.745	.192	.730
161	.922	.254	.168	.356	.160	.515	242	.391	.130	.204	1.325	.253	.770
162	.746	.254	.136	.356	.160	.531	243	.442	.130	.298	1.355	.253	.790
163	1.807	.154	.852	.933	.303	1.187	244	.463	.130	.312	1.325	.253	.800
164	1.488	.154	.703	.933	.303	1.091	245	.592	.100	.682	2.274	.529	1.344
165	1.474	.154	.696	.933	.303	1.086	246	1.024	.223	.234	.427	.160	.480
166	1.109	.154	.525	.933	.303	.980	247	.604	.100	.696	2.274	.529	1.334
167	1.487	.223	.344	.449	.192	.702	248	1.258	.223	.228	.200	.128	.504
168	1.375	.223	.314	.449	.192	.702	249	.557	.158	.463	1.617	.253	.731
169	1.104	.223	.266	.449	.192	.680	250	.541	.158	.450	1.617	.253	.723
170	.959	.223	.220	.449	.192	.650	251	.573	.158	.476	1.617	.253	.738
171	1.880	.140	1.100	1.154	.354	1.480	252	.627	.120	.882	2.756	.529	1.344
172	1.706	.140	.995	1.154	.354	1.400	253	1.362	.270	.380	.544	.192	.587
173	1.500	.140	.875	1.154	.354	1.350	254	.687	.120	.964	2.756	.529	1.295
174	1.442	.140	.862	1.154	.354	1.300	255	1.543	.270	.432	.544	.192	.609
175	1.104	.140	.645	1.154	.354	1.160	256	.211	.056	.337	1.179	.710	1.430
176	1.499	.202	.624	.556	.224	.835	257	.194	.100	.699	1.011	.253	.794
177	1.455	.202	.611	.556	.224	.828	258	.082	.154	.217	.435	.202	.584
178	1.256	.202	.355	.556	.224	.735	259	.186	.068	.405	.430	.885	1.735
179	1.077	.202	.305	.556	.224	.705	260	.139	.086	.297	1.373	.441	.993
180	2.211	.356	1.494	1.277	.256	.830	261	.070	.134	.020	.563	.253	.724
181	1.247	.184	.620	.662	.236	.912	262	.191	.043	.529	5.502	1.062	2.120
182	.919	.184	.310	.662	.236	.840	263	.179	.076	.158	1.749	.529	1.264
183	1.993	.135	2.173	2.160	.441	1.856	264	.661	.118	.022	.718	.373	.850
184	2.197	.211	.991	.886	.253	.920	265	.235	.073	.497	4.170	.710	1.220
185	2.609	.211	.907	.886	.253	.892	266	.050	.130	.034	1.325	.253	.627
186	1.681	.304	.370	.427	.190	.578	267	.211	.063	.603	5.630	.885	1.510
187	1.375	.223	.314	.450	.160	.557	268	.113	.112	.104	1.789	.441	.778
188	1.555	.100	.790	1.011	.160	.550	269	.043	.168	.012	.764	.253	.565
189	1.728	.304	.380	.427	.180	.538	270	.203	.050	.734	7.153	1.062	1.266
190	1.899	.187	1.092	1.131	.303	1.104	271	.181	.099	.210	2.274	.529	.968
191	2.204	.170	1.565	1.401	.354	1.490	272	.065	.154	.031	.933	.303	.660
192	1.805	.170	1.284	1.401	.354	1.324	273	.231	.089	.601	5.097	.710	1.070
193	2.202	.100	1.117	1.011	.354	1.590	274	.106	.158	.589	1.617	.253	.544
194	2.618	.154	.546	.415	.204	.990	275	.226	.076	.714	6.793	.885	1.340
195	2.749	.187	.392	.483	.199	.807	276	.139	.135	.135	2.159	.441	.675
196	2.500	.223	.252	.200	.128	.600	277	.202	.068	.894	8.671	1.062	1.668
197	1.500	.112	1.352	1.789	.441	1.650	278	.196	.120	.280	2.756	.529	.843
198	1.949	.175	.724	.735	.253	.974	279	.116	.187	.069	1.131	.303	.565
199	2.082	.212	.529	.501	.199	.784							
200	1.650	.252	.297	.353	.160	.610							
201	1.599	.158	1.312	1.617	.353	1.155							
202	1.370	.135	1.499	2.159	.441	1.463							
203	1.515	.211	.686	.886	.253	.805							
204	1.603	.256	.497	.904	.199	.835							
205	1.448	.140	.846	1.154	.354	1.300	285	1.855	.288	1.647	1.697	.045	.500
206	1.646	.100	.836	1.011	.353	1.470	286	1.786	.257	1.401	1.513	.045	.508
207	1.398	.100	1.011	.353	.353	.980	287	1.568	.207	.978	1.217	.045	.520
208	2.589	.154	.540	.415	.202	.980	288	1.396	.161	.658	.949	.045	.559
209	1.471	.154	.307	.415	.202	.837	289	2.941	.190	.415	.280	.018	.404
210	1.199	.223	.121	.200	.128	.597	290	3.645	.450	1.960	1.202	.120	.575
211	1.398	.158	1.150	1.517	.441	1.465	291	1.082	.413	1.486	.913	.109	.526
212	1.399	.223	.121	.200	.128	.597	292	1.148	.392	.910	.854	.087	.428
213	1.960	.112	.868	1.789	.441	1.320	293	3.093	.350	.684	.432	.087	.482
214	1.939	.175	.720	.734	.253	.970	294	3.151	.191	.229	.270	.087	.654
215	1.336	.175	.498	.734	.253	.845	300	1.919	.461	1.263	1.189	.069	.380
216	1.119	.175	.447	.734	.253	.801	301	1.814	.395	.996	1.019	.069	.392
218	1.419	.212	.643	.886	.354	1.250	302	1.650	.323	.721	.832	.069	.413
219	.941	.140	.551	1.154	.354	1.095	303	1.616	.303	.684	.432	.069	.413
220	.723	.140	.424	1.154	.354	1.003	304	2.286	.242	.228	.168	.036	.392
221	1.674	.252	.302	.353	.160	.613	305	2.523	.400	.322	.247	.168	.413
							306	3.972	.360	.225	.113	.131	.510



